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Nuclear fuel cycle and reactor strategies: Adjusting to new realities

Contributed papers

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FOREWORD

The International Symposium on Nuclear Fuel Cycle and Reactor Strategies: Adjusting to New Realities was held from 3 to 6 June 1997 in Vienna, Austria. It was organized by the International Atomic Energy Agency (IAEA) in co-operation with the European Commission, the Nuclear Energy Agency of the OECD (OECD/NEA) and the Uranium Institute (UI). More than 300 participants from more than 40 countries and 5 organizations took part.

The reason for organizing the symposium was to face the new realities in the nuclear fuel cycle and to come to conclusions on how these new realities should be addressed. In the light of these objectives, international working groups prepared key issue papers on six topics that were selected as the central themes for consideration at the symposium. An International Steering Group composed of the representatives of 12 countries and three international organizations co-ordinated the work of the six working groups.

Working Group 1 on "Global Energy Outlook" established assessments of the scenarios of future requirements for nuclear energy to provide a basis for the work of the other Working Groups.

Working Group 2 on "Present Status and Immediate Prospects of Plutonium Management" dealt with the problems arising from growing stocks of separated plutonium, both from civilian and military programmes.

Working Group 3 on "Future Fuel Cycle and Reactor Strategies" discussed the factors influencing future reactor and fuel cycle concepts and the resulting trends for the next 50 years.

Working Group 4 on "Safety, Health and Environmental Implications of the Different Fuel Cycles" assessed and compared the overall environmental and health effects of different systems of the nuclear fuel cycle.

Working Group 5 on "Non-proliferation and Safeguards Aspects" discussed the existing non-proliferation regime and new initiatives. Furthermore, it considered non-proliferation aspects for different fuel cycle options and for nuclear materials declared excess to defense needs.

Working Group 6 on "International Co-operation" assessed the types of international co-operative activities and arrangements and drew conclusions for the future.

Each of the six working groups wrote a key issue paper. These key issue papers are published as a separate publication.

During the symposium, addresses and papers presented by leading experts and policy makers provided additional information in these fields. The key issues were explored further in discussions by the participants and a panel of experts, which helped to highlight the main problems to be addressed in designing the policies for the nuclear fuel cycle in the next 50 years. Special emphasis was placed on the problem of disposition of separated plutonium of civil origin and of plutonium originating from the dismantlement of nuclear weapons.

This TECDOC contains all the papers presented, together with a summary of the symposium and a list of participants.

EDITORIAL NOTE

CONTENTS

Opening Session

Session I

Session II

Session III

Session IV

Session V

Session VI

Closing Session

OPENING SESSION

OPENING ADDRESS

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Introduction

The concept of the nuclear fuel cycle emerged almost as early as the concept of using controlled nuclear fission to generate electricity. It was widely believed, amongst the scientific and technical experts of that time, that a *closed* fuel cycle would be the most desirable option: spent fuel from power reactors would be reprocessed and recovered plutonium would be recycled as fuel for fast breeder reactors. Not only the experts but also people outside the technical elite were impressed by the promise that the closed cycle would offer.

In the late 1970s the International Nuclear Fuel Cycle Evaluation (INFCE) was conducted. Forty countries and four international organizations were represented. By this time we were looking at a gradually maturing technology which had produced "new realities" in terms of the technical aspects of the fuel cycle, its economics and its proliferation aspects. INFCE showed that effective measures can and should be taken both at the national and international levels and agreements worked out to minimize the danger of proliferation of nuclear weapons - without jeopardizing energy supplies or the development of nuclear energy for peaceful purposes. The results of the INFCE, many of which are still valid today, were published in eight Working Group papers.

Some 20 years have elapsed since this study was carried out. During this period further "new realities" have emerged, which could not be foreseen, and it seems appropriate again to consider various aspects of different nuclear fuel cycle options. That is why we are here today. The intention is certainly not to repeat a comprehensive study like INFCE. Rather, in preparation of this Symposium, the IAEA Secretariat, in co-operation with Member States and international organizations, has made efforts to address some *specific* issues concerning the nuclear fuel cycle. The results of these efforts will be presented and reviewed during this Symposium.

What are the further "new realities"?

Let me briefly point to some significant "new realities".

1.   The nuclear power projections have been lowered

A first "new reality" is that over the past 20 years, the projections for global nuclear electricity production in the year 2000 have been progressively revised downwards. In 1980, when the INFCE study was performed, world nuclear power capacity in the year 2000 was predicted to be between 850 and 1200 GWe. However, at the end of 1996 the world's net nuclear capacity stood at only 351 GWe and it is almost certain that it will not be greater than around 380 GWe by the turn of the century. Prospects for nuclear power development beyond the year 2000 are different for different regions. Growth of nuclear power is now envisaged mainly in Asia, Central and Eastern Europe and in some developing countries. In the Western countries the nuclear industry is reorienting towards provision of services. The lower than expected demand on uranium in combination with revised estimates of cost-effective resources means that uranium supplies will last much longer than earlier calculated

2. General development of FBR's deferred

A second "new reality" is that a commercialization of fast breeder reactors has not occurred. Only France, Japan and Russia, strongly committed to nuclear power, continue to develop fast reactor technology and India and China are also engaged in the development of this technology for future deployment. In addition, experimental studies are in progress aimed at using this technology in the near-term for utilizing plutonium stocks and burning minor actinides, while reserving for the future the option of breeding.

3. Closing the fuel cycle

A third "new reality" is that the closed fuel cycle has not taken hold. Until the early 1970s, many envisaged the nuclear fuel cycle of the future to be an orderly sequence of processes beginning with uranium mining, milling and conversion followed by fuel enrichment, fuel fabrication, and power generation. This cycle would then be completed by reprocessing, recycling of plutonium and uranium to fast reactors. Closure of the fuel cycle would result in the effective use of plutonium, and minimization of waste. In short, there would be a long-term, competitive, if not cheap, source of energy, with the added bonus of a high degree of energy independence once all components were in place.

The present situation at the back-end of the fuel cycle differs dramatically from that vision. Because of the delay in fast reactor deployment, the once expected closed fuel cycle for fast reactors has not become a commercial reality, even though it has been successfully demonstrated on a rather large scale in France and at an experimental level in Russia, the USA, Japan, India and the UK.

Meanwhile, the feasibility of recycling plutonium in the form of MOX fuel in existing light water reactors has been demonstrated at the industrial level in a few industrialized countries. While the advocates of a closed cycle consider this step to be only a temporary expedient until fast reactors are available, others consider it a necessary method for consuming civil and military plutonium stockpiles

It is now generally agreed that direct disposal is a feasible option for spent fuel management for countries choosing this path. At the same time, studies are in progress in some countries to define new closed cycle strategies which would minimize the transuranic element content for final disposal.

4. Defence sector nuclear material must be taken care of

A fourth "new reality" is that with the end of the Cold War, the USA and Russia have begun to reduce their nuclear arsenals and that other NWS may - in due course - follow this lead. Disposal or use of the fissile materials coming from the defence sector - so far expected to be more than 100 tonnes of Pu and several hundred tonnes of HEU is a new - welcome - challenge.

5. Other developments

Lastly, we must take note of the "new reality" that there are a number of States, especially in Central and Eastern Europe, which have a substantial nuclear power share, but little or no infrastructural support for the back-end of the fuel cycle. We must also note that delays in the establishment of final storage facilities and the emergence of a global market for fuel cycle services, including reprocessing, are other significant realities in fuel cycle developments during the past 20 years.

The foregoing "new realities" have resulted in the following matters of relevance:

There is an adequate supply of uranium for the foreseeable needs of the current types of reactors;

There is a growing accumulation of separated plutonium;

There is a growing accumulation of spent fuel;

There is a debate on advantages and disadvantages of different fuel cycle strategies. This debate includes consideration of the related economic, environmental and proliferation issues;

There is consideration of the possibility of regional and international co-operation aimed at an economically effective way of resolving plutonium and waste management issues.

Let me briefly comment on these points, one by one.

1.   Uranium demand and supply

The uranium supply and demand situation has been monitored on a continuous basis and has been reported periodically since 1965 under the title "Uranium Resources, Production, and Demand" - commonly known as the "Red Book". It is a joint publication of the IAEA and Nuclear Energy Agency (OECD). For its reporting of reasonably assured resources (RAR), the Red Book has adopted a maximum production cost of US $130/Kg for uranium as the criterion even though the value of the dollar has decreased by 50% since the 1977 edition.

During the INFCE evaluation in 1980, RAR at $130/kg of uranium amounted to 2.59 million tonnes. In 1995, they were estimated at 2.95 million tonnes of uranium, capable of meeting nearly 50 years of future global requirements at present level of consumption.

In reality the price of uranium fell steadily from its level in 1980 (US $88/Kg) to its lowest spot market price of less than US $18/Kg in 1994. The price has since increased to US $30/Kg. In 1996, annual world demand for uranium was about 62 000 tonnes while only 36 000 tonnes were produced. The deficit was met by reducing stockpiles. The price increase resulting from the supply/demand gap seems likely to result in a rapid increase in supply. It is believed by experts that substantial new uranium resources can be discovered once exploration is re-activated as a result of a higher uranium price.

Although there appears thus to be an adequate supply of uranium at least until 2050, substantial exploration activities need be conducted to identify and evaluate so far unknown resources. A reliable database on uranium resources and supply is essential when considering future nuclear fuel cycle options. The question of plutonium use will be critically influenced by how long the supply of uranium to fuel nuclear power reactors can be assured.

2.   Accumulation of separated plutonium

Early in the development of nuclear power, and against the background of the projections of world nuclear power capacity and the development and deployment of fast breeder reactors, commitments were made to construct and operate reprocessing facilities. However, the lower than expected growth rate of nuclear power capacity and the delays in development of fast breeder reactors created a significant imbalance between the rate of plutonium separation and the rate of

plutonium utilization. With inventories of separated plutonium accumulating, it was proposed to use the separated plutonium in MOX fuel for light water reactors. Perhaps it should be noted parenthetically that the use of plutonium for energy generation is not something new. In fact, nearly 40% of the electricity produced by each thermal reactor fuelled by uranium is due to fission of plutonium isotopes, accumulated during uranium burning.

In 1996, 22 tonnes of plutonium were separated and 8 tonnes of plutonium were used in light water reactors and fast reactor development programmes. The imbalance over earlier years between the separation and use of plutonium had resulted in a global inventory of separated civil plutonium of about 160 tonnes at the end of 1996. The inventory may go up to 170 tonnes in the next couple of years before starting to decrease gradually to about 140 tonnes in 2015. I should add, however, that the projections of inventory after 2000 have significant uncertainty.

In addition to civil plutonium, highly enriched uranium and plutonium coming from the defence sector are likely to influence decisions on fuel cycle options for some decades to come. Under the START I and II treaties, many thousands of American and Russian nuclear weapons are slated to be retired within the next decade. As a result, at least 50 tonnes of plutonium on each side are expected to be removed from military programmes, along with hundreds of tons of highly enriched uranium. The availability of this surplus material for peaceful use constitutes another "new reality" for the nuclear fuel cycle, as well as an element to consider from the point of view of national and international security.

3.   Spent fuel accumulation

It is estimated that more than 100 000 tonnes of spent fuel from power reactors will have to be stored in facilities throughout the world by the year 2000. Less than 40% of the amount generated annually will be reprocessed by then. The rest will be stored for a long period before being finally disposed of in geological repositories or before being sent for reprocessing. Because many countries have yet to decide how they will ultimately deal with spent fuel, issues relating to long-term storage of spent fuel are becoming more and more important.

The IAEA estimates that about 50 tonnes of plutonium is contained in the spent fuel discharged from nuclear reactors world-wide in 1996 and that the annual production figure will remain more or less the same until 2010. The cumulative amount of plutonium produced in nuclear power reactors worldwide was less than 1 tonne in 1960, about 13 tonnes by 1970, about 124 tonnes by 1980, about 490 tonnes by 1990 and will be about 1010 tonnes by 2000.

Conflicting views

It is clear that if we use uranium in a once-through fuel cycle, accumulation of spent fuel - and plutonium - cannot be avoided. The plutonium removed from the military sector will add further to the quantities accumulated.

As you know, current thinking about disposition goes in two directions. One suggests that for the foreseeable future plutonium has no economic value as an energy source. Accordingly, in this view, the most economic process is to dispose of the spent fuel in a safe way. The other line of thinking essentially advocates the closed nuclear fuel cycle concept. The difference of opinion stems in part from the different expectations of nuclear electricity growth and the availability of economical supplies of uranium. However, the difference also has significant roots in different assessments of security and environmental issues.

Among the factors of relevance for the discussion is the public perception of plutonium. Plutonium is feared on several grounds: terrorists might get Pu through trafficking, proliferation-

bent regimes might obtain it to make weapons. Another fear is that plutonium could be dispersed into the environment in the event of an accident. In addition, a tendency to generally "demonize" plutonium makes rational public debate about plutonium difficult.

At junctures like this, an expedient solution may for some countries be simply to buy time. Defer decisions. One such solution is for States to store the spent fuel containing plutonium in a safe and secure way over a period of time until they are ready to decide. This preserves the option of using plutonium as an energy source at some future point of time when perhaps other energy sources, including uranium, might be scarce. Perhaps you could call this a no-regret solution: You would not now incur the cost of reprocessing and the problem of having to guard separated Pu. You would have less problems to reprocess after a number of years if you were to choose that option. And should you after a number of years wish to dispose of the fuel as waste, this would also be easier.

Ideas at the governmental level

Let me now refer to some discussions of the issue pursued between governments and in the IAEA.

In 1992, Mr. Dircks, then Deputy Director General of the IAEA, discussed the potential global political and security problems connected with the accumulation of separated plutonium from civilian programmes and from possible warhead dismantling. There were also a few *meetings* within the IAEA with some Member States to discuss these issues. In that connection the concept of an International Plutonium Storage, dormant since the mid 1980s, was touched upon. More recently a Group of nine States formed a Working Group independent of the IAEA and drafted international guidelines for plutonium management to enhance transparency and build confidence. I understand that Mr. Agrell, the chairman of the Working Group, will make a presentation on the results of the Group's work during this Symposium.

The *NPT Review Conference held in 1995* called for greater transparency in the management of plutonium for civil purposes, including public information about quantities and about the relationship of stocks to national nuclear fuel cycles. The Conference called also for continued international examination of policy options concerning the management and use of stocks of plutonium, including the option of an arrangement for the deposit with the IAEA, and the option of Regional Fuel Cycle Centres.

The participants in the *Moscow Summit* on Nuclear Safety *in the spring of 1996* pledged "support for efforts to ensure that all sensitive nuclear materials designated as not intended for use in meeting defence requirements are safely stored, protected and placed under IAEA safeguards as soon as it is practicable to do so". While recognizing that the primary responsibility for the safe management of weapons fissile material rests with those States which have produced and possess it, the Summit participants also stated that "other States and international organizations are welcome to assist where desired".

In the autumn of 1996, following up on the Moscow Summit, an "International *Experts Meeting* on safe and Effective Management of Weapons Fissionable Materials Designated as No Longer Required for Defence Purposes" was held *in Paris*. The IAEA was represented, together with seven countries and the European Union. It might be noted that this was the first meeting at which a basically bilateral Pu issue was discussed in an international format. The IAEA used the occasion to describe its experience and expertise in matters relevant to international plutonium management.

In January 1997 the *USA announced* a dual path policy in which excess weapons plutonium will either be burned as MOX in LWRs or will be vitrified.

Another important development to note is the so-called *trilateral initiative* of US, Russia and IAEA at the General Conference last autumn on verification of nuclear materials removed from the defence sector. It was agreed jointly to explore the technical, legal and financial issues connected with the verification of such materials. As you may know, the Agency is already engaged in the verification of nuclear material removed from weapons programmes in the USA. The trilateral initiative aims at conclusions on how the Agency could perform verification in similar ways in both the US and Russia.

Future developments in the nuclear fuel cycle can - and probably will - differ from country to country. Your discussions, I hope, will help us to better define the problems and possibilities better.

Role of the IAEA

What should be the role of the IAEA? The Agency's programme in the field of nuclear fuel cycle must reflect the realities facing the international community today, including the security and commercial impacts of ex-weapons material. The activities must also be geared to promoting further the reliability, safety and economic viability of nuclear power.

The traditional verification function will remain an essential part of the Agency's role. The same is true of the function of the IAEA to provide a forum for exchange of experience in the nuclear fuel cycle. Additionally, the involvement of the IAEA in possible international co-operative programmes for the disposition of plutonium might help to make such programmes more effective. In fact, some Member States have urged the IAEA to play a co-ordinating role in international activities on plutonium disposition.

I believe that this Symposium is a good forum for discussion among Member States and I hope that the six Key Issue Papers which summarize a common international understanding of the various nuclear fuel cycle issues, including technology, safety, safeguards, environmental and institutional aspects, will be basic reference points on the subject.

Many Member States of the Working Group preparing for this Symposium are of the view that a continued dialogue following the Symposium would be desirable. If it were generally thought useful, the IAEA could explore suitable steps to ensure the exchange, on a continuing basis, of basic information on major developments and economic and programmatic information on the nuclear fuel cycle. This could include consideration of advantages and disadvantages of different fuel cycle strategies of plutonium and waste management. The latter issue might play an important role in the future development of nuclear energy.

Using the Agency as a means for elaborating *international norms* should also be examined. The Agency has already published three safety guides on interim storage of spent fuel from power reactors. They cover the design of spent fuel storage facilities, preparation of safety analysis reports and the safe operation of spent fuel storage facilities. Preparation of a safety document on the safe handling of plutonium is nearing completion.

The new reality of a "plutonium pressure" might perhaps also suggest to Member States that the Agency could help co-ordinate international efforts to promote transparency. I leave that to your discussion.

ACKNOWLEDGEMENTS

I would like to conclude by thanking the Working Group members, the chairmen, the members of the Steering Group and the Scientific Secretaries for hard and invaluable work to prepare this Symposium. I welcome all the participants and wish you progress and success in discussing the difficult subjects before you.

OPENING ADDRESS

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I am very glad to be with you for this important Symposium and grateful for the opportunity to address you in this opening session. This meeting is one more sign of the close co-operation between the NEA and the IAEA. I should like to congratulate the IAEA for its initiative in setting up this Symposium. Its main theme -- the place of plutonium in the development of nuclear energy -- is a topic ripe for discussion.

As demonstrated quite clearly in the papers which have been prepared for this symposium, this is an opportune moment to discuss the reality of the need to address the disposition of stocks of separated plutonium. This issue is even more important given the availability of plutonium coming out of military programmes over the next few years.

There is real public concern about this issue. An important underlying fact is that the need for the deployment of fast breeder reactors is not now seen to be imminent. In some countries, however, the back end of the fuel cycle has already been developed with a view to using such reactors, and reprocessing plants are already functioning. It is this that has led to concerns over the emergence, in some countries, of plutonium in excess of current requirements. Some separated plutonium is being turned to good use as MOX fuel, but the associated development of plutonium transport and trade is also a matter of public concern. It is not surprising that these concerns have emerged, and it is the job of governments, with the help of the IAEA and the NEA, to show the public that these concerns are being met by the necessary investment and operational choices in the nuclear industry, and by the implementation of appropriate policies and institutional controls.

Over the next few days you will be hearing a lot more about the emergence of the plutonium stocks and the responses to this development. However, in the next few minutes I would like to concentrate on a few other realities that I believe define the broader context within which the development of nuclear energy will take place in the coming decades. Specifically, I will address the deregulation of energy markets and nuclear energy research and development: two areas that the NEA has been studying.

Liberalization of Energy Market

The liberalization of energy markets is an important new reality that will be affecting most countries. The process has developed further in some of the OECD countries than elsewhere. but many of the countries which previously had centrally planned economies have announced plans for radical reform along similar lines. To a great extent. markets for coal and oil have been as open as other commodity markets, but for a long time, in many countries, it was assumed that the production and supply of grid-based fuels, gas and electricity, was necessarily so structured that there was a natural monopoly. This belief led to a high degree of state ownership, or regulation by public authorities, of generation and supply.

Although considerable evolution has taken place recently in attitudes toward the role of government, there does not appear to be movement toward total deregulation of the energy industries. Recent economic analysis has, however, indicated ways in which markets can operate where supply was previously regulated. The economic efficiencies that can be expected from the operation of market forces are enormously attractive and it is not surprising that governments should seek to obtain these benefits. The arguments in favour of liberalization are so broadly based that even the likelihood of particularly adverse consequences for the economic viability of nuclear energy will not prevent the growing acceptance of this approach to energy policy.

The likelihood that market liberalization will have adverse impacts on nuclear energy is linked to the capital-intensive nature of this means of electricity generation, the long periods over which a return on the investment has to be sought, and the current availability of alternative technologies that provide good economic returns over much shorter periods. There can be no doubt that for some years to come it will be difficult to make an economic case for new investment in nuclear generation if the bases for comparison of fuel costs are not radically altered. For existing nuclear plants that are in good condition and well operated, the outlook should actually be positive in economic terms: their marginal operating costs should be extremely competitive. We have already seen. however, that the cost impact of replacing a major component such as a steam generator can quickly lead to a decision to take a plant out of service.

One characteristic of markets is that they tend to emphasize short-term rather than long-term interests. A very small number of governments are in the fortunate position of being able to rely on a number of energy sources that will provide viable options for a considerable period, and for them there is little incentive to consider the longer term. Another characteristic of markets is that they do not automatically lead to the satisfaction of public policy goals other than the reduction of the price of the good being traded. Modifying market behaviour to produce other benefits is usually complex and difficult.

Even where governments have few options, they will not automatically look to a long-term commitment such as a nuclear plant as a solution. The political climate may not be conducive, uncertainties remain with respect to evaluating the wider benefits of nuclear energy, and budgets are tight everywhere.

Change in Perception of Role of Government in Nuclear Development

Compounding the difficulties for nuclear power developers and operators resulting from the move towards market liberalization is another reality. It is now over fifty years since the first demonstration of nuclear fission, and almost forty-one years since the first connection of a nuclear generating plant to a public supply grid. There is, therefore, a school of thought that says that the nuclear industry is now mature and should be totally self-reliant for its future development.

Governments have already invested a lot of money to provide the basic science and technology for nuclear energy, and in many cases that investment has extended, directly or indirectly, to the power plants themselves, as well as a wide range of fuel cycle facilities. With hindsight, questions are raised as to whether it was necessary to spend so much, so soon, particularly with respect to fast breeder reactors. We do not need, however, to go back many years to see that, in a very different context of prospects of inadequate energy supply, before the significant development of offshore oil and gas reserves, government investment in nuclear R&D was thought to be well-justified. Nevertheless, the questions are real and widespread as to the need for continued government engagement in the development of nuclear energy technology.

Evolution of Nuclear Research Institutes

One effect of this change in attitudes toward the role of government can be seen in the substantial evolution in organizations originally established as national or regional nuclear research institutes. Not long ago the NEA made a study of more than 40 nuclear research institutes in 17 Member countries of our Agency, together with those of the European Commission. We discovered that many of the institutes had undergone a great deal of diversification. Sometimes this was out of necessity, but it was also a tribute to their success in amalgamating many research disciplines to provide results that could be exploited in various areas of industry, medicine and agriculture. In a few cases there was a subsequent re-focusing on nuclear R&D, with the spin-off of non-nuclear competence to other institutes or to newly created commercial organizations.

Overall, the budgets of these institutes have been growing or stable, with one or two exceptions. This broad picture, however, hides some more interesting tendencies, which, from the point of view of the managers of the institutes, may have seemed somewhat less than bright.

First, there has been increasing reliance on non-government sources of funding. In all 34 cases for which data are available, the entire funding initially came from governments, either as base funding or through contracts, with more than 80% as base funding in most cases. By 1991 there were 8 cases where the non-government funding was at least 30%, and there had been a marked increase in the amount of government funding as contracts. Many of you know the problems of conducting a long-term research programme under such conditions.

Second, from the standpoint of nuclear development, the remarkable diversification, particularly after 1970, has resulted in non-nuclear research taking up a significant share of the overall budget. In fact, in the case of 28 institutes non-nuclear research accounted for over 40% of the budget by 1991.

Third, a growing proportion of nuclear R&D budgets has to be devoted to decommissioning and cleaning up facilities, leaving even less for further development and exploration. This need to decommission research facilities is, nevertheless, a basis on which to develop methods for decommissioning reactors and other large-scale nuclear facilities.

Fourth, while the number of persons employed tended to grow throughout the period, with scientists and engineers gradually becoming a higher proportion of the staff, the percentage of staff over 40 also has grown markedly.

Fifth, it is clear that the facilities in many institutes are also coming to the end of their working lives. A separate, more detailed study by the NEA, has demonstrated that this is certainly the case for the facilities needed for nuclear safety research.

There is no evidence that private funding of nuclear R&D has compensated for the reduced funding by governments, and overall there has been a noticeable erosion of the infrastructure needed to maintain a viable nuclear option for the future. I should add that the reduction of government funding for nuclear R&D is only one part of a general trend to reduce spending on all sorts of energy R&D, although the reduction for nuclear energy has been more severe.

Energy Policy Objectives

For most governments the aim of energy policy is to achieve a balance between three objectives: economic efficiency in the supply and use of energy: security of energy supply both for the short and long term: and, avoidance of damage to the environment. In recent years there has been increasing emphasis on the environmental objective. Talk in some circles of a "gas bubble" meanwhile led, during the late 1980's, to some reduction of interest in the security of supply issue. This evolution of attitudes is a rational response to the reality that there is currently available a more than adequate supply of relatively cheap fuels, while there is growing appreciation of the actual, as well as the potential, long-term environmental damage that their use can cause.

The case for nuclear energy is that it can support all three of the general energy policy objectives. Take, first, the economic objective. In several countries a new nuclear plant would still be the least-cost choice for augmenting base load capacity. More generally, the fact that a quarter of the OECD's electricity, and about 17% of the world's, is generated from nuclear energy, cannot but have a depressing effect on the price of competing fuels. Although a calculation of the size of this effect is fraught with difficulties, the benefit to economic development is far from negligible. For the future, the enormous potential energy source that is represented by the stocks of already mined and

processed uranium, and the known resources of natural uranium, sets a cap on the costs of electricity supply, and eventually on the costs of a wider range of energy services.

My colleagues in the OECD International Energy Agency have never taken their eyes off the target of security of energy supply, but the subject is receiving added emphasis as their projections indicate the likelihood that remaining hydrocarbon reserves will be concentrated into restricted regions of the world, particularly the Middle East, within the next few decades. It is, of course, the case that several prominent Member countries of the NEA and IAEA have already made clear their belief in the current need for nuclear energy as a provider of security of energy supply. I expect that they will be joined by others before too long.

I sense also that there is an increasing willingness among politicians to consider the merits of nuclear energy with regard to environmental protection, even though there is an understandable preoccupation with the difficulties of finding socially acceptable sites for the disposal of radioactive waste.

In summary, for the major part of the world, the outlook for nuclear energy appears more promising from a long-term perspective than over the next decade or two. The challenge, then, is to find means to preserve the nuclear option for the future. The challenge more particularly for international organizations such as the IAEA and the NEA is to help their Members deal with the important issues that lend themselves to being addressed through international co-operation.

I am glad to assure everyone here of the high degree of co-operation that already exists between the NEA and IAEA. There is clear evidence of this co-operation in the use made of results from NEA studies in preparing several of the Key Issues Papers. In particular, I would like to mention the contributions we have been able to make based on our work on technology for plutonium management and on fuel cycle economics, and, indeed, the assistance provided by experienced NEA staff members in the preparation of this Symposium.

I also am interested in the question raised in Key Issue Paper Number 6, of a mechanism for continued work on programmatic and economic information in relation to the nuclear fuel cycle. This is an area where there has already been a very marked degree of co-operation between the two Agencies. The Nuclear Development Committee of the NEA has been very pleased to have the IAEA's input to the formulation of its programme of studies on the fuel cycle. At the working level there has been frequent close contact and exchange of information between the Secretariats. The IAEA Secretariat has always been invited to join the expert groups that prepare our consensus reports and has participated most constructively in them. For several years now this co-operation has been enhanced by the practice of inviting experts from non-OECD countries into most of these groups. I look forward to continuing this highly beneficial practice and to seeing our co-operation become even more effective.

OPENING ADDRESS

G. Clark
Secretary General,
Uranium Institute,
London

It was a great honour for the Uranium Institute to be asked to co-sponsor today's Symposium. We did so gladly. The Institute, as I am sure most of you know, is the leading non-governmental global organization representing companies involved in the nuclear fuel cycle. We have getting on for eighty corporate members from more than twenty countries and areas, most of whom are taking part in the Symposium. Our Members are drawn from all the processes in the cycle, from the mining of raw uranium, through the manufacture of nuclear fuel and its use for generating electricity, to the treatment and disposal of the spent fuel at the end of the cycle.

We are as you will readily appreciate the practitioners who operate the cycle. The subjects which the Symposium will cover are of great interest to us for technical and commercial reasons as well as scientific and political. If you consider them in order, everyone of them covers an area which is fundamental to the well being of the Uranium Institute's member companies.

The Global demand for energy is our starting point. Uranium is a fuel as well as a rare metal. Demand for it is more influenced by the cross-currents in the fuel market than by the mining cycle, but the latter influence our ability to meet demand. Likely demand for energy over the next fifty years as set out in the first Key issues paper conveys rather an encouraging message to the uranium miners: both the need for the product and the resources are there.

KIP 2 is the core of this conference. It deals with plutonium. The wildest things are said in the world outside about plutonium, most of them untrue. The attitude of the nuclear companies is rather more sober. For us it is an inevitable by-product of uranium based fuel. It is a benefit: 30-50% of the energy given off by a power reactor comes from the fissioning of the plutonium which is formed by neutron capture along the way. Some of it is left when the time comes for replacing the fuel loadings with fresh fuel. What to do then is a matter of controversy and debate. Some of the UI 's Members see advantage in recycling the plutonium residues and the unused uranium from spent fuel as the constituents of a further fuel material, MOX. Others do not. It is not entirely a question of economics. Politics and conservation as well as non-proliferation considerations come into it. The balance of advantage is by no means clear cut, and varies with local conditions. It is splendid, and very much a benefit that here in Vienna we shall discuss these questions with some of our collective prejudices set aside. The aim is to let light into dark places.

It is so easy to get these things wrong. Just as Klaproth was influenced in 1789 in his choice of name by the discovery some years earlier of the planet Uranus, so Glen Seaborg wanted to commemorate the discovery in 1930 of the planet Pluto, discounting perhaps the hellish connotations of that name from Greek mythology. Would there be quite so much mythologizing of Plutonium if it had been named Seaborgium?

KIP 3 takes the resource implications of the first paper, and applies them to likely developments in reactor technology over the next half century. We have a great interest in that. Seen from an industrial perspective nuclear power is a mature technology. It has emerged from the experimental phase when every reactor was different as clever engineer designers tried a new gismo to get better results to a situation where two or three models of thermal reactor have proved reliable and repeatable, and are thus widely installed. Even so the nuclear business is still a long way short of imitating the highly automated assembly lines now universal in many other industries (such as motor manufacture), and could make significant cost savings if it moved determinedly down that path. More important over the next fifty years we need to investigate innovative technologies which will

overcome the problems raised by the existing ones, such as the Rubbia concept of accelerator supplied neutron streams, or the work at Karlsruhe in burning plutonium in inert matrices. I hope that our discussions on this paper will avoid the trap of assuming that the future will inevitably be a more refined version of the past, and allow some creative thinking.

KIP 4 on radiation protection is of vital importance to us. The regulations laid down by the Safety Inspectorate in all nuclear countries, following the Framework Convention or the recommendations of the ICRP, rule our operations. The work force moreover is much more affected by the effectiveness of the regulations than anyone else: they work inside power stations, fuel fabrication plants or at the mine, and their families live in the vicinity. Added to that the work-force apply the regulations.

The civil cycle industries have as much at stake in non-proliferation and safeguards as anyone (KIP 5). The existence of a reliable international system of surveillance and control, in which the public has confidence is an essential pre-condition for the smooth running of the civil cycle. This is an area which has gradually emerged from the "top-secret, burn before reading" culture of the cold-war into the more business like world of international trade. Now that bomb making has become unfashionable the only possible large scale use for uranium is as the raw material for nuclear fuel. It is in our commercial interests to apply the international safeguards system assiduously and conscientiously. Our practical experience of operating the system needs to be taken into account when considering the implications of new developments, such as MOX, or when assessing the real risks of proliferation.

Finally as an international organization the Uranium Institute is of course in favour of international co-operation in nuclear development (KIP 6). This is a world wide business. No one country is self sufficient in nuclear materials and technologies, not even the United States, whose uranium production declined spectacularly in the 1980s. The paper for your consideration devotes much space to descriptions of bureaucratic mechanisms. I leave you with two thoughts: ordinary commercial considerations might lead to the same result with a much less burdensome superstructure; but if we are to leave these things to the market it is essential to rig the market first so that it delivers the result we want. For the second reason I very much welcome the discussion.

OPENING ADDRESS

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1. On behalf of the European Commission, I wish to congratulate the organizers and contributors to this symposium for their courage in trying to look 50 years ahead and this in a field which is strongly influenced by public opinion rather than by expert judgements. I would therefore like to welcome you to this nuclear vision conference.

2. None other than St. Paul, in his letter to the Thessalonians, tells us: 'Do not despise prophetic talks'; and Antoine de Saint-Exupery supports the idea that decision makers should have clear visions and look into the future, because 'Each strong vision becomes reality'.

3. We in the European Commission, have a considerable interest in such a vision being developed at global level. The European Union, at the turn of the millennium, is still an important net importer of energy. Only just over 50 % of the total energy consumption is produced in the European Union and the tendency is that this internal production rate will decrease rather than increase. Nuclear energy accounts for about 33 % of the electricity production, in Europe with 145 operational nuclear power plants generating a total of 120 GW electric.

   The European Union operates the largest industrial nuclear fuel cycle which involves an active and job creating export sector based on the highest technical and safety standards.

4. The Euratom Treaty, which was signed 40 years ago, has provided the basis for a series of activities aimed at creating a strong European nuclear industry devoted to the safe and peaceful use of nuclear energy.
   Among these activities, wide ranging research and development programmes have been carried out either in the Joint Research Centre or through shared cost actions, bringing together industry, licensing authorities, research centres and universities from different countries of the EU.

5. The central objective of these R & D activities has been to enhance safety, competitiveness and the protection of man and the environment from radiation. This central objective has been complemented by five other goals:

   • Maintaining scientific and technical expertise throughout Europe;

   • Supporting policies of the European Union in the nuclear area, including provision of scientific/technical expertise to other Commission services dealing with energy policy, nuclear safeguards, nuclear safety, environment and external relations;

   • Promoting harmonization and standardization within the European Union;

   • Ensuring support to ambitious, long lasting projects still far away from the market,(a long way from being exploited on the market) such as fusion research;

   • Last but not least, supporting the effective and efficient use of human resources and large-scale advanced facilities.

6.   Multiannual Framework Programmes for Research and Technological Development constitute the legal and financial base for R & D activities at the level of the European Union. The current 4th Framework Programme, covering the period 1994 - 1998, has an overall financial envelope of 14 billion ECU, of which about 10 % is devoted to nuclear research. A Fifth Framework Programme covering the period 1998 - 2002 is currently under discussion.

7.   How should we orient our research in the future? Although the European nuclear industry has proven its maturity, it remains necessary to pursue the development of nuclear technology in three major directions:

-    environmental protection
-    energy security
-    economic competitiveness

8.   Furthermore, the growing awareness of the risks of climatic change has led to the recognition that nuclear energy has the advantage of being able to produce large and economic quantities of energy with no CO_2 emissions, in accordance with the recommendations of the Rio and Berlin conferences on climatic change.

9.   The development of safe, competitive and acceptable nuclear power plants requires a determined and continuous effort at world level based on specific research and development programmes, focused on precise objectives. The European Union intends to bring its specific contribution to the overall effort.

10.   Which reorientations are we considering for this contribution? The proposed contents of the emerging 5th Framework Programme give some indications in this respect. While we intend to maintain some continuity with the past, there will be a number of major changes with regard to the substance and to the management of the 5th Framework Programme. The new programme will be, for example, more strongly oriented towards the economic and social needs of the EU (employment, quality of life and competitivity).   Increasing attention will be given to support the innovation potential of the European industry. The programme will be focused on a few key areas and improved methods will be implemented for its effective management.

      The nuclear programme, which was primarily safety-driven during the last 15 or 20 years, should pay more attention to competitiveness. Existing installations are confronted with increased competition arising from deregulation and from 'cheap' fossil-based cogeneration plants. Consequently, research should focus on those issues critical for extending the safe operation life of installations and for providing additional margins of competitiveness, notably through the development of improved fuels.

11.   The European nuclear industry for its part, is responding to new market opportunities in Asia and emerging countries. Maintaining Europe at the forefront of nuclear technology requires continuous commitments to develop appropriate and diversified solutions for meeting these needs in the context of an increasingly competitive global market.

12.   Nuclear research must address in a more explicit and coherent fashion, short, medium and long term needs and objectives linked to the prospects of growing energy demand world-wide and the increased concern about global warming. This means, in particular, that research should consider not only incremental or evolutionary improvements to the existing nuclear fuel cycle but also the exploration of more radical and innovative concepts, like new reactor and fuel cycle concepts, actinide incinerators, etc.

13. The proposal, released in April of this year for the 5th Framework Programme under the Euratom Treaty, comprises the new ideas I have just mentioned within the following major activities:

- A key action devoted to nuclear fusion, with the long term objective of building an experimental reactor followed in the future by a demonstration reactor;

- A generic activity in the area of nuclear fission including innovative features related to reactor safety, safety and security of the nuclear fuel cycle and radiation protection;

- An activity dedicated to support the access and use of large research infrastructures.

14. These activities would be implemented through various modalities, shared cost actions on the one hand, and the recourse to the JRC, as a centre of competence, to provide independent and neutral expertise at a European level, on the other hand.

The financial amount to be requested for this programme has not yet been fixed; in relative terms, nuclear R & D should remain at about 10 % of the total financing of R & D under the 5th Framework Programme.

15. Concentrating on the nuclear fission part of the proposed 5th Framework Programme, I would like to analyse briefly the contents of the various areas covered by the Commission's proposal. These areas relate to:

- Operational safety of existing facilities and severe accidents;

- Security and safety of the fuel cycle radiation protection;

- Innovative concepts;

- Nuclear material safeguards;

- Cooperation with Central and Eastern Europe and the countries of the former Soviet Union;

- Support for research infrastructures.

16. <u>Operational safety of existing facilities and severe accidents</u>

This area includes issues related to the extension of the lifespan of reactors, to the technological aspects of severe accidents, as well as to strategies and methods for the management of accident and post-accident situations.

Specific points may be:

- Measures to maintain and improve the safe operating life of existing plants and competitivity;

- Integrity of equipment and structures, including the understanding of ageing mechanisms and material behaviour;

- Irradiation embrittlement and radiation damage, techniques for non-destructive examination;

- Modernization of plant control and monitoring systems;

- Basic phenomenological issues in the area of severe accidents, prevention and mitigation strategies of severe accidents;

- Enhancement of passive safety features;

- Improved understanding of behaviour of fuel under high burnup.

17.   Security and safety of the fuel cycle

The work in this area should contribute to a joint, scientifically sound approach to the management, minimization and disposal of radioactive waste. In view of the number of nuclear facilities now in operation, it is particularly important to avoid and reduce the production of radioactive wastes and to reduce to the greatest extent possible their radiotoxicity in the long term.

More specific topics may include:

- R & D and demonstration on advanced fuel aimed at minimizing waste production;

- Basic nuclear data related to fuel cycle safety and security;

- Improved recycling techniques for plutonium and other radioactive nuclides;

- Safety examination of plutonium recycling for existing and new reactor concepts;

- Development of advanced forms of waste treatment, including

   - further improvement of volume reduction techniques, such as compaction, concentration, incineration, etc.

   - further improvement of waste conditioning and packing techniques, such as drying, coating with cement vitrification, drumming in order to reduce waste volumes;

- Performance and characterization of waste forms and packages;

- Tests of recycling of minor actinides and long-lived fission products;

- Further exploration of final storage concepts.

18.   Radiation protection

The emphasis here will be on the understanding and awareness of the hazards related to ionizing radiation, more particularly the effects of low-dose radiation, the management of nuclear emergencies and the restoration of contaminated environments.

Specific topics may include:

- Improved understanding and quantification of risks of radiation, especially for low and protracted exposures;

-   Further improvement of the management of potential nuclear emergencies and strategies for the restoration of contaminated environments including radioecology;

-   Improved understanding of perceptions of risk and how risk can be more effectively communicated to better inform policy makers;

-   Enhancing safety and efficacy of other uses of ionizing radiation in industry and medicine.

19.   Innovative concepts

This area will focus on studies on new nuclear facilities, advanced and more efficient fuels, future systems and concepts to increase the safety of the complete nuclear cycle and the competitiveness of industry, in particular, in relation to outside markets. The work shall include safety analysis, impact on man and the environments and the most promising approaches from a technical and economic viewpoint in a sustainable development perspective.

Specific topics may include:

-   Innovative reactor concepts with higher safety levels and/or possibility for heat and power co-generation;

-   Innovative reactor concepts based on fast neutrons and new heat-carrying fluids, small reactors for external markets;

-   Improved materials for reactor vessels and other components (increased wear, radiation and corrosion resistance, limited activation);

-   Extended operating life of new Nuclear Power Pluto;

-   New fuel/fuel assemblies with

    -   minimization of plutonium and minor actinide production

    -   in-situ fission product trapping improved fuel cladding (less corrosive)

    -   lower operation temperatures or higher thermal inertia

    -   cermet, ceramic fuel cladding, coated particles.

20.   Nuclear Material Safeguards

This area includes the development of technologies and methods to meet the new challenges: strengthening of IAEA safeguards, changes in the nuclear fuel cycle, the rise of the stock of fissile materials due to nuclear disarmament, the illicit traffic in fissile materials.

Specific topics may be:

-   Improvement of high performance trace analysis and environmental monitoring techniques;

-   Nuclear forensic analysis for detection of origin, intended use and transfer routes of seized materials, including nuclear material data bank;

- Improvement of non-destructive and destructive analysis techniques and volume measurement techniques for unattended operation in different fuel cycle facilities;

- Further development of digital, sensor triggered, integrated containment and surveillance systems for various applications;

- Remote monitoring and interrogation techniques, authentication and encryption techniques, potential of multimedia applications;

- Performance assessment and quality control of measurement systems and intercomparison exercises, standardization.

21. Cooperation with Central and Eastern Europe and the countries of the former Soviet Union

The objective here is to encourage cooperation in research/development activities to increase nuclear safety of reactors, waste management, radiation protection and the control of fissile materials. The prospect of the future enlargement of the European Union towards East European countries is of immediate relevance in this context. Better coordination and integration between research and technical assistance programmes such as PHARE and TACIS will be fostered.

22. Support for large research infrastructures

Some research test facilities are indispensable for the further development of nuclear energy. The European Union has to maintain a certain number of specific and well-equipped facilities, for example, to qualify new industrial applications, to examine operational problems encountered or to provide new basic nuclear data. The Commission therefore intends to support the optimum utilization of such infrastructures in its new Framework programme

Conclusions

23. Energy is a strategic factor in the competitiveness and growth of the European economy. The future of nuclear power will be closely related to the safety records of the industry and to its competitiveness in relation to conventional power plants, especially those fired with natural gas. In the medium term, in view of decreasing fossil fuel reserves, possible political instability in some areas of the world and increasing environmental concerns, nuclear and renewable energy sources are likely to become of growing importance.

24. The 5th Framework Programme ahead of us intends to provide significant support to the development of safe and competitive nuclear technologies. The decline in national nuclear research programmes and the closure of some national facilities are a particular concern. There is a strong (great, vital) need to maintain the existing know-how and experience of nuclear industry. The 5th Framework Programme could play an important role in preserving this expertise. This reinforces the view that there should be a greater integration of European nuclear research in order to avoid duplication and to enable the Union to make best use of diminishing resources.

The Community has always actively participated in and supported international nuclear cooperation and has a number of important agreements and assistance programmes in such key areas as nuclear safety, safeguards, non-proliferation and trade.

The Commission considers that efficient and effective international regimes for nuclear safety, safeguards, physical protection and non-proliferation will and must remain a permanent reality for the safe and peaceful use of nuclear energy in the future.

SESSION I

ALTERNATIVE LONG TERM STRATEGIES FOR SUSTAINABLE DEVELOPMENT: RAPIDLY INCREASING ELECTRICITY CONSUMPTION IN ASIAN COUNTRIES AND FUTURE ROLE OF NUCLEAR ENERGY

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Abstract

Many people in the world express the concern that global warming will become an increasingly serious problem. A rapid increase in population and demand for energy in the Asian region must be discussed in this context. Despite the forecast of an increase in demand for energy, the Asian region is short of oil and natural gas resources. In addition, only less energy can be supplied by renewable energy sources in the Asian region than in the other regions because of high population density. Nuclear energy is an important energy resource for fulfilling the future increasing energy demand in the Asian region and for contributing to the suppression of carbon dioxide emissions. In the Asian region alone, however, we cannot rely limitlessly on LWR which does not use plutonium. According to a scenario analysis, the total capacity of nuclear power plants in the Asian region would reach large scale and the cumulative amount of demand for natural uranium will increase to about 5 million tons in the Asian region alone. Just the nuclear power plants of this scale in Asia alone will rapidly consume the world's cheap natural uranium resources if we rely only on natural uranium. In the Asian region, few countries have embarked on nuclear power generation and the capacity of equipment is still small. Currently, however, many plans for nuclear power generation are being designed. Many Asian countries obviously consider nuclear power generation as a valid option. Many potential policies must be examined in the light of future uncertainty. In the future, both renewable energy and nuclear energy must be resorted to. When nuclear energy is utilized, the use of plutonium and FBR in the Asian region must be taken into account in order to attain continual growth and development.

1. INTRODUCTION

Many people in the world express the concern that global warming will become an increasingly serious problem. A rapid increase in population and demand for energy in the Asian region must be discussed in this context. For example, it is forecast that the population in the Asian region will account for more than 50 percent and a demand for primary energy will reach about 35 percent in the world totals (Response Strategy Working Group / IPCC, 1990).

Despite the forecast of an increase in demand for energy, the Asian region is short of oil and natural gas resources. In addition, only less energy can be supplied by renewable energy sources in the Asian region than in the other regions because of high population density. Moreover, energy supply to the Asian region is accompanied by many difficulties, which will be amplified if the use of coal resources found relatively abundantly in the Asian region is restricted by problems with global warming. The problems with global warming must be met by all countries in the world and, therefore, it is not only the Asian region that must always address those problems. It is, however, important that the Asian countries also suppress the discharge of greenhouse gases wherever possible. Furthermore, it is desirable that the share of the Asian region in the use of fossil fuel does not increase significantly. Many investigators have discussed the future image of energy supply and demand in the world. On the basis of this discussion, this report clarifies conditions of the future growth and development of the Asian region in the light of its characteristics.

2. ENERGY DEMAND GROWTH IN ASIAN COUNTRIES

The demand for energy per capita in the Asian region is currently relatively low. On the other hand, a number of actions can be taken to save energy in the Asian region. For example, the iron and cement industries consume much energy and those industries in the Asian region are inferior to their counterparts in the other regions in terms of energy consumption efficiency. The efficiency

could be enhanced technologically by 30 or 40 percent (IEA, 1994, 1995). In addition, market principles have not completely penetrated many Asian countries, which might save more energy through the introduction of market principles in the future.

We must not, however, overestimate this energy saving. In the Asian region as well, current state-of-the-art equipment implements moderate energy consumption efficiency. Moreover, some technological limits cannot be overcome because of the wall of theoretical efficiency. This means that energy can not be saved limitlessly. Macroeconomically speaking, energy consumption per GDP differs by no more than 30 percent between the Asian developing countries and developed countries. [1] (See Figure 1.)
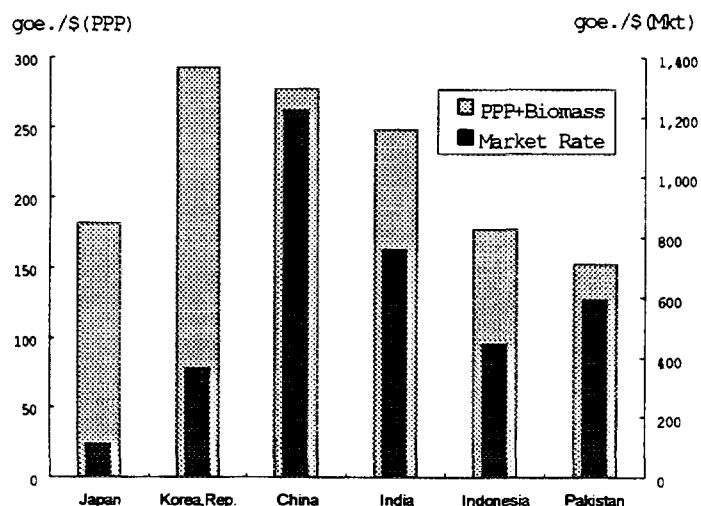
FIG. 1. Primary energy consumption per capita of Asian countries

Many investigators have made simulations of how demand for energy in the Asian countries will develop usually based on energy - GDP relations. A possible means for such simulation is to use energy demand on a per capita basis (electric power demand/fuel demand) as the index. The use of energy demand per unit of GDP as the index, which is often adopted, is accompanied by difficult problems with international GDP comparisons. (The use of PPP leads to the problem of whether the currency value can be fully converted.) The use of a demand for energy on a per capita basis as the index is exempted from those problems. This index provides relatively stable, intuitively understandable data despite differences in climate conditions and population density between countries.

Furthermore, the equilibrium point of long-term energy demand, which may be expressed by per capita energy consumption, should be taken into account rather than the rate of increase in demand in order to more effectively examine sustainability.

Figures 2 and 3 illustrate results of estimating energy consumption from a population forecast by the World Bank, as well as the high growth accelerated policy scenario of IPCC/RSWG. The "Potential" in this estimation are calculated by assuming that direct fuel demand and electric power demand on a per capita basis in 2100 in the OECD countries are realized in all regions. The assumed direct fuel demand and electric power demand on a per capita basis in 2100 in the OECD countries are 0.48 and 1.37 times higher than in 1985, and 0.45 and 1.11 times higher than in 1994, respectively in the RSWG/IPCC scenario. Even if the OECD countries experience a significant economic growth in the future, the electric power demand on a per capita basis will level off, and the fuel demand will be significantly lowered depending on the development of energy saving.

30

According to the assumption on which these Figures are based, there is a huge potential of energy demand in the Asian region even though we assume a considerable energy consumption.

3. ENERGY SUPPLY IN ASIAN COUNTRIES

3.1. Fossil fuels

In the Asian region, relatively abundant coal, some natural gas, and limited oil reserves are found as fossil fuel resources (see Fig. 4) . Although the Asian region is relatively rich in coal resources, the coal quality is not necessarily good, and it is not easy to develop coal resources because of a poor transportation infrastructure. Naturally, an increase in coal consumption is likely to lead to global warming. Excessive dependence on coal would, therefore, significantly boost costs to counter global warming.

Natural gas resources are found in Indonesia, Malaysia, Myanmar, Thailand and other countries. According to a past survey, however, those countries are not rich in reserves of natural gas.

3.2. Renewable energy

Following are some brief comments on renewable energy resources, which are not abundant in Asian countries.
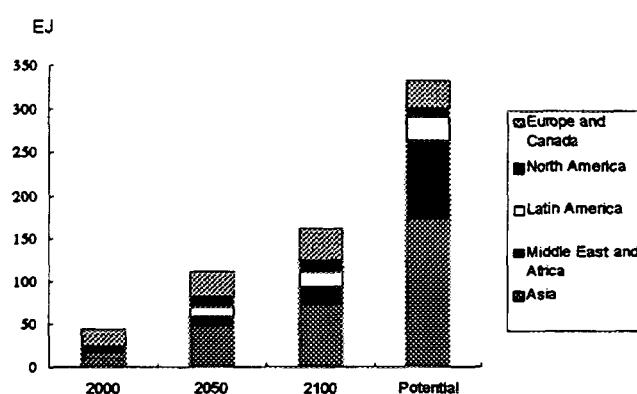
FIG. 2. Electricity consumption
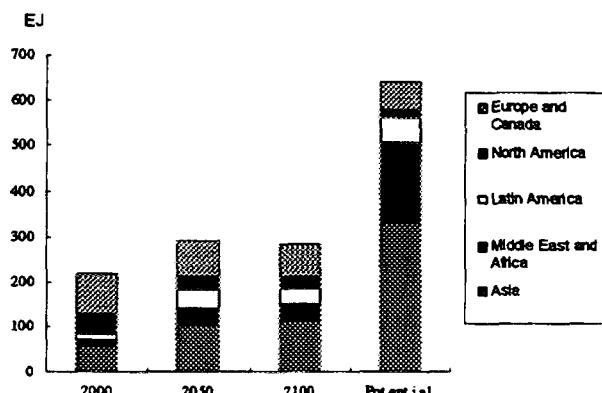
FIG. 3. Secondary fuel consumption
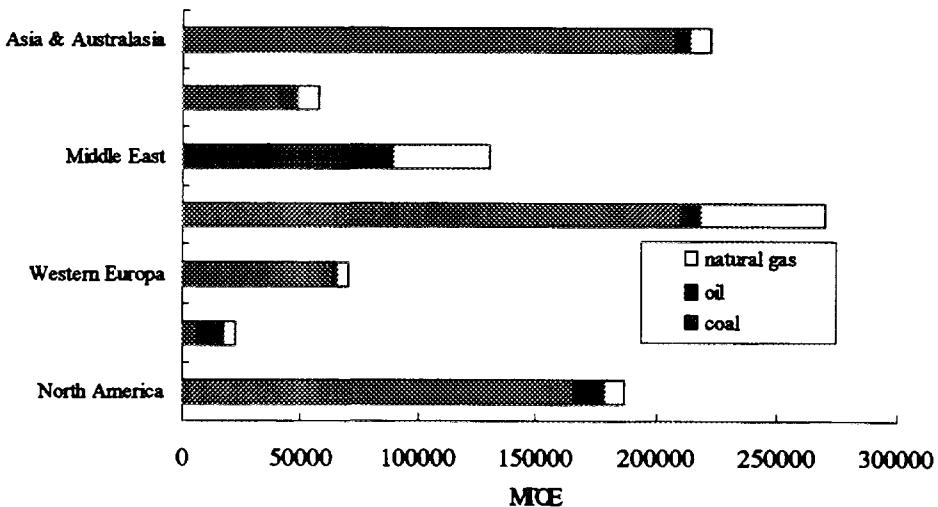
FIG. 4. Fossil fuel reserves in the world

3.2.1. Hydro

A number of large-scale hydroelectric dams including Sanxio Dam in China have been planned and designed in the Asian region. Apart from China, the Mekong basin and other basins have abundant water resources. Mini hydro power plants have been utilized actively to electrify agricultural villages, and the technically exploitable potential is about 4,330 to 5,340 TWh (Burnham 1993) . Thus, more hydraulic energy may be exploited in the future. Even if about 50 percent of this potential energy is developed (OECD's present level), however, these energy resources cannot cover the electric power demand that will rise in the future.

3.2.2.   Intermittently renewable energy

The Asian region is wealthy in intermittently renewable energy resources for power generation (solar and wind). Because of high population density and the centralization of population in urban areas in the Asian region, however, the use of intermittently renewable energy must be restricted.

For example, in Japan, equipments for photovoltaic cells (PV) must be installed on limited open spaces, such as roofs or walls of buildings, soundproof walls on streets, slopes of banks, as well as lakes, ponds and bogs. In addition, estimates show that the potential supply from photovoltaic cells (PV) hardly exceeds 200 GW. In Japan, the utilization rate of PV is about 12 percent because of climatic conditions, which means that electric power from PV will not be more than 210 TWh. This value does not reach even 25 percent of the present Japanese power demand. Moreover, since the actual use of lakes, ponds and bogs may have an adverse impact on the environment, not all the equipment for 200 GW can be introduced. In Japan, the actual extension of solar optical electric conversion to such a large scale may result in an increase in costs and carbon dioxide emission [2]. (See Figure 5.)

Wind is often used to generate electric power. In particular, India has a number of wind power stations, and China plans the development of wind power generation of 2 GW by 2010. But the relative volume of wind power generation is small compared with its total electricity consumption.

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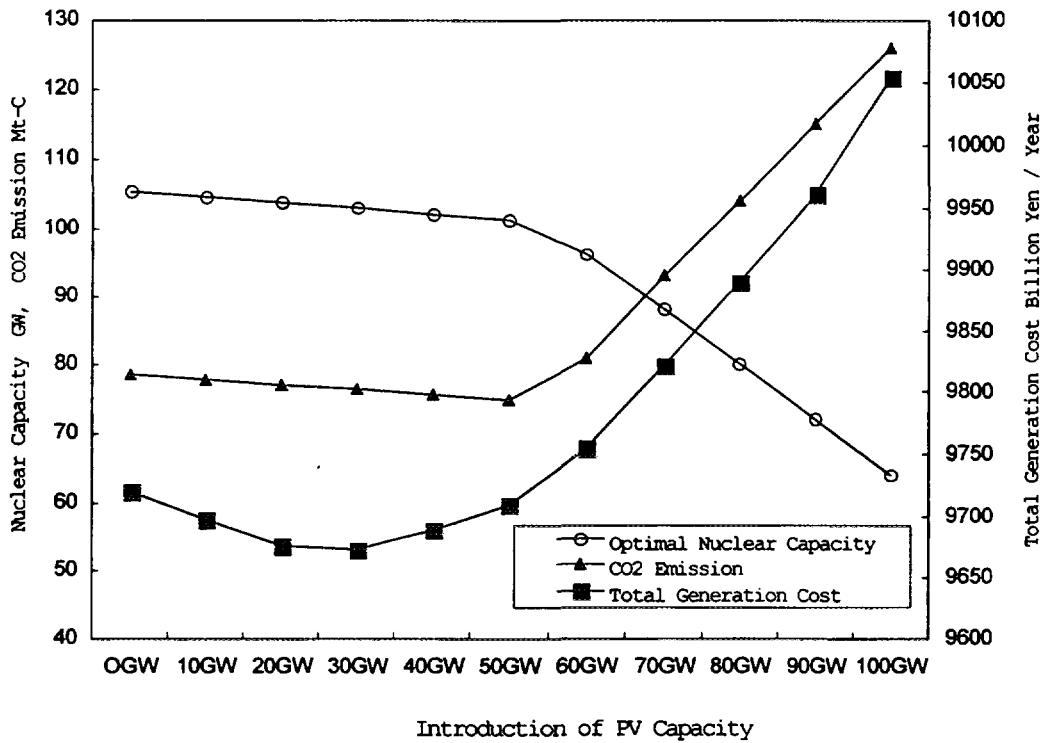
FIG. 5. CO_2 emission, power generation cost and optimal nuclear introduction of PV in Japan

3.2.3. Biomass

In the Asian region, the development of biomass resources must also be restricted. Soil has been eroded significantly, and many cultivated fields have been lost because of urbanization. An important issue in Asian countries is to procure food or to prevent an increase in food imports. In China, India and other countries, many trees have been planted, but forestry has been destroyed gradually. Because of high population density, reduction in cultivated fields resulting from urbanization must restrict biomass resources available on a per capita basis.

3.2.4. Others

In the Asian region, the Pacific volcano belt provides geothermal resources. Japan, the Philippines and Indonesia are rich in geothermal resources. China also has geothermal resources in the southeastern part, and in Tibet geothermal power plants rated at 25 MW are installed. A report shows that geothermal power generation of 400 to 590 MW will have been developed by 2020, but the volume of geothermal power generation will still be small.

China has tidal power resources, and Japanese may be able to use wave power These power plants can, however, be implemented only at limited sites.

We can thus conclude that the supply of renewable energy will be restricted in the Asian region. Figure 6 gives us an image of the renewables supply potential in Asia, it shows the result of dividing the possible supply of renewable energy (in 2050) used for electric power generation covered in Burnham 1993 by population in each region. This literature provides a scenario based on the assumption that as much renewable energy as possible will be introduced in the light of some regional characteristics. The scenario can, therefore, be regarded as approaching the upper limit of introduction of renewables. It also reveals that a significantly small volume of renewable energy will be introduced for electric power generation on a per capita basis in the Asian region as in the Middle East and Africa.

4.   ENERGY SUPPLY/DEMAND BALANCE IN ASIA

As shown above, demand for and supply of energy in the Asian region are characterized by the following:

• In the future, the population will have increased considerably and demand for energy will grow significantly;

• Coal resources will play a major part in energy supply;

• Renewable energy resources can be used in limited amount.

The following scenario developed in IEEJ 1995 reflects those characteristics. It covers China, India, Indonesia, Japan, Pakistan, Bangladesh, Vietnam, the Philippines, Thailand, Korea, Taiwan, Malaysia, Myanmar, Sri Lanka, Nepal, Hong Kong and Singapore. This analysis estimates the future demand for energy for each country. It supposes that an increase in energy demand in the Asian region in the future will be accompanied by significant energy saving. (Energy intensity will be reduced by 1.5 percent per year.) It also sets low economic growth for the Asian region. (The economic growth rate of the whole Asian region is 6.2 percent in 1992 to 2010, 3.7 percent in 2010 to 2030, and 2.4 percent in 2030 to 2050.) The rate of electrification in the Asian region, which is currently low, is assumed to reach 35 percent by 2050. This scenario presumes that electricity will
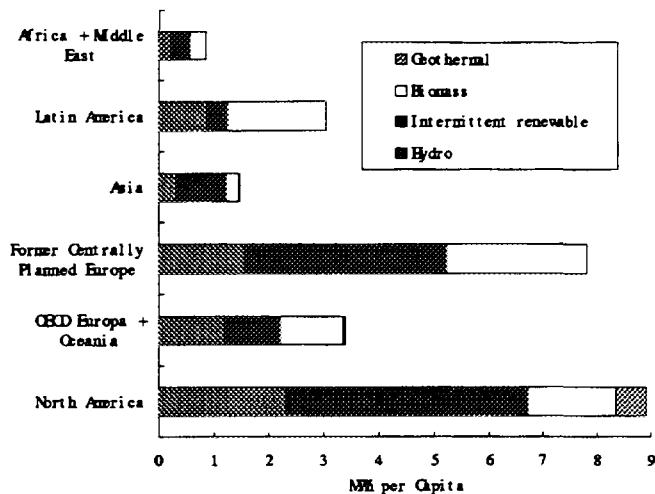
FIG. 6. Per capita renewable energy supply for electricity generation
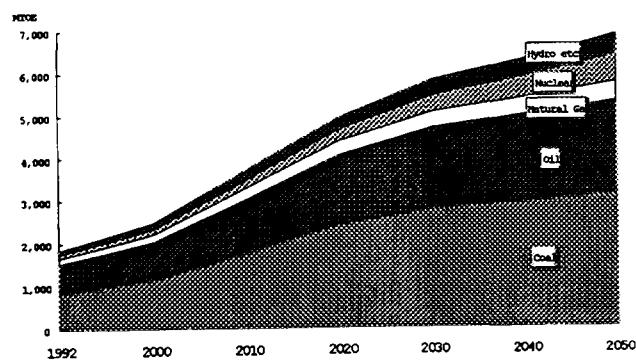
FIG. 7. Energy demand in Asia for nuclear 20% scenario
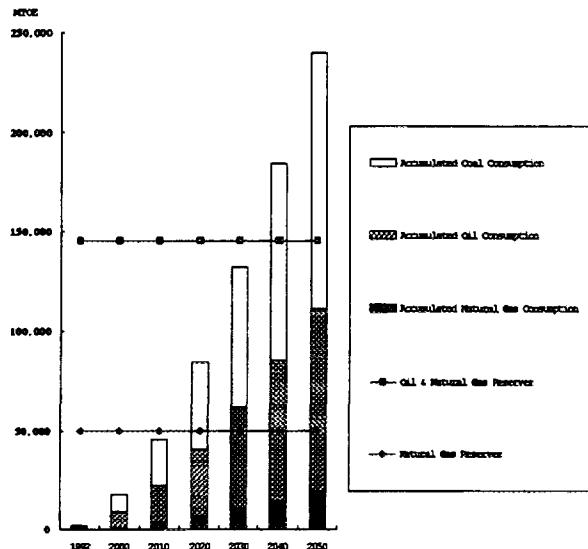
FIG. 8. Accumulated fossil fuel consumption in Asia and fossil fuel reserves in Asia and Middle East
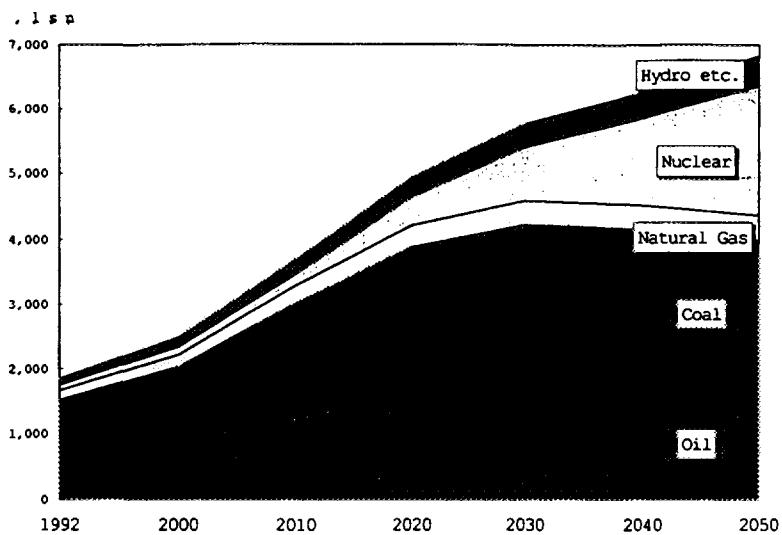
FIG. 9. Energy demand in Asia for nuclear 60% scenario

be covered mainly by hydraulic power plants, coal fired power plants and nuclear. This presumption is based on the following considerations:

• The Asian region is short of fossil fuel resources other than coal.

• Oil resources will become insufficient because of the possible development of motorization in the future.

• The introduction of a large amount of natural gas for electric power generation would make Asian countries depend more heavily on the Middle East.

• LNG to be imported could be handled at limited appropriate sites.

• The implementation of renewable energy other than hydraulic power must overcome restrictions in terms of costs which are not sufficiently low.

35

Figure 7 showss the energy demand in the Asian region reflecting this scenario and presuming that nuclear power generation is 20 percent of total power generation (in 2050).

According to this scenario, demand for fossil fuel in the Asian region will rise considerably. As shown in Figure 8, the cumulative consumption of oil and natural gas in the Asian region will rapidly approach the limits of oil and natural gas reserves in Asia and the Middle East toward 2050.

The scenario illustrated in Figure 9 for encouraging the introduction of nuclear power aims at preventing an increase in fossil fuel consumption. It assumes an enhancement of the ratio of nuclear power in total electric power generation to 60 percent in 2050. Energy consumption in this scenario is based on the assumption that the rate of electrification in 2050 is 50 percent. This scenario estimates that the consumption of fossil fuel in the Asian region will decline from around 2030.

Figure 10 shows carbon dioxide emissions for each of the above scenarios. In each scenario, carbon dioxide emissions will increase to a much higher level than the current one. If the introduction of nuclear energy is accelerated, however, carbon dioxide emissions will decline from around 2030.

Unlike some literature, the above scenarios are not based on a high energy saving rate that has not been attained historically. They also do not suppose any significant introduction of renewable energy other than hydro power. In light of the present political and economic climate, these scenarios can be said to reflect greater efforts than are currently being made to save energy, and existing energy resources in the Asian region.

Furthermore, the scenarios will not be essentially modified even if such small-scale renewable energy as is found in rural areas in China and India is actively introduced.

The intended suppression of fossil fuel consumption shown in Figure 9 to the current level would require the introduction of renewable energy equivalent to the present energy consumption in the Asian region, and this introduction can not be readily implemented.
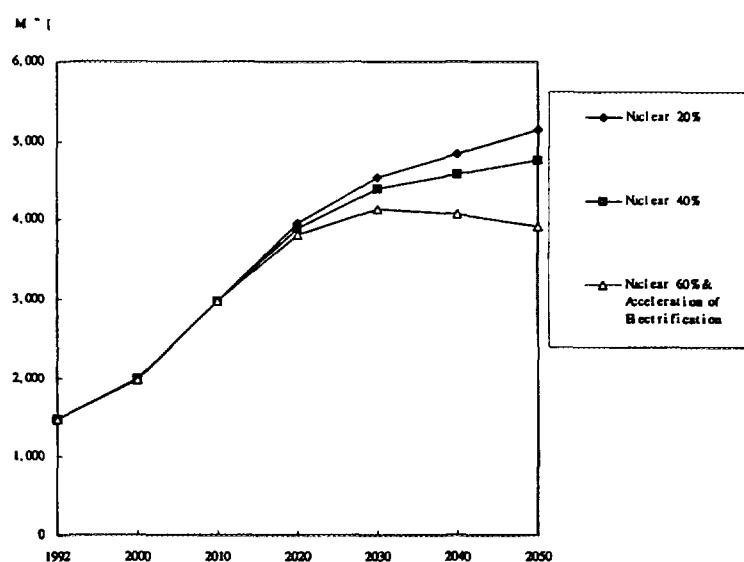
FIG. 10. Future CO_2 emission in Asia for three scenarios

36

5. ROLE OF NUCLEAR POWER IN ASIA

As shown above, nuclear energy is an important energy resource for fulfilling the future increasing energy demand in the Asian region and for contributing to the suppression of carbon dioxide emissions. In the Asian region alone, however, we cannot rely limitlessly on LWR which does not use plutonium. According to the scenario which assumes that the amount of nuclear power generation will account for 60 percent as a result of rapid electrification, the total capacity of nuclear power plants in the Asian region would reach 1,340 GWe. Figure 11 shows that the cumulative amount of demand for natural uranium will increase to about 5 million tons in the Asian region alone. Moreover, in 2050, the annual amount of demand for natural uranium will reach 250 thousand tons (if no plutonium is used).

While reserves of uranium are not well known, just the nuclear power plants of this scale in Asia alone will rapidly consume the world's natural uranium resources if we rely only on natural uranium.

In the time frame shown in Figure 11, the use of plutonium and FBR provides no significant effects. This is because it is not assumed that plutonium and FBR are used in the whole Asian region and because FBR will be used from around 2030. Naturally, the use of plutonium and FBR will contribute considerably to the effective utilization of uranium resources. In addition, the volume of wastes to be disposed of could be reduced significantly.

To actually facilitate the above mentioned nuclear power development requires a continuing reliance on nuclear power generation and high economic efficiency. In the Asian region, few countries have embarked on nuclear power generation and the capacity of equipment is still small. Currently, however, many plans for nuclear power generation are being made. (See Table 1.) Many Asian countries obviously consider nuclear power generation as a valid option.
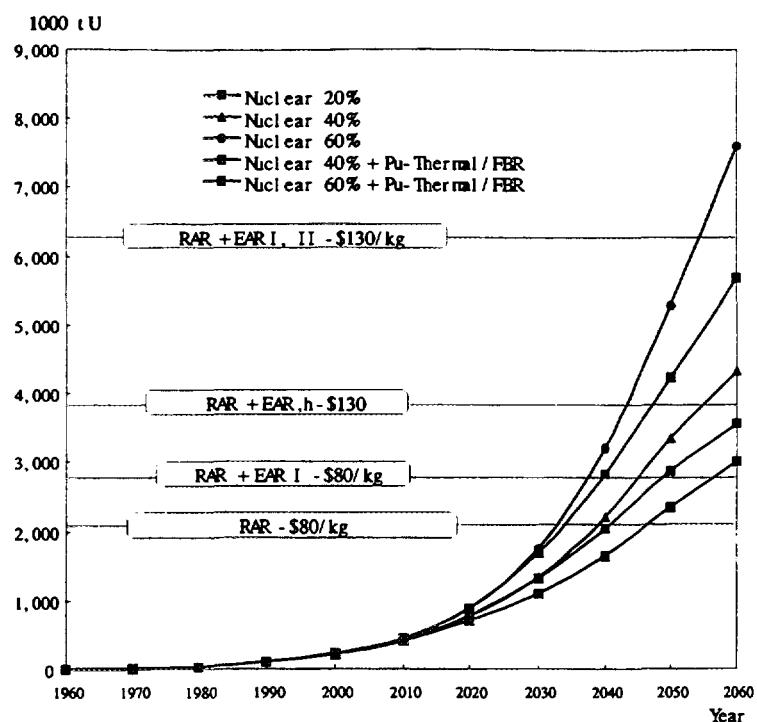
FIG. 11. Accumulated natural uranium demand in Asia for nuclear scenario

37

TABLE 1-A: TRENDS OF NUCLEAR POWER DEVELOPMENT IN ASIAN COUNTRIES

Country		No. of reactor	10,000 kW	Trends
South Korea	Running Under construction Under planning Total	2 2	200 200	- A long-term nuclear power plan developed in December 1995 reports that 28 plants offering 26,329 thousand kW will have started operating by 2010. - The target has been the domestic procurement of nuclear power technologies. Now, almost all steps from design to production are covered domestically. The Korean nuclear power industry intends to offer information on nuclear power to other countries. - Such organizations as Korean Electric Power Company, Korean Heavy Industry Company and Korean Nuclear Power Laboratory have assumed tasks for developing specialist fields, contributing to the attainment of achievements. (About 75 percent of the shares of Korean Electric Power Company are owned by the Government. Korean Heavy Industry Company is a subsidiary of Korean Electric Power Company.)
Taiwan	Running Under construction Under planning Total	6 0 2 8	514 0 260 774	- No domestic nuclear power industry exists. All nuclear energy is imported. - The introduction of nuclear power has met with strong opposition. In May 1996, GE became the successful bidder on the Ryuhmon ABWR project, which was closed by the diet. But, the bill for closing the project has been upset by a motion, with the project budgeted. - Part of the primary system is offered by Toshiba and Hitachi under GE. The secondary system is offered by Mitsubishi Heavy Industry.
China	Running Under construction Under planning Total	3 4 8 15	227 17 720 1264	- According to the ninth five-year plan developed in 1996, nuclear power of 20 and 25 million kW is to be implemented by 2010. - The standard reactor type to be introduced is PWR. Other reactor types may, however, be adopted if required financing and economic conditions are met. (Actually, CANDU and Russian PWR have been introduced.) - The Chinese Government has undertaken the domestic procurement of PWR, actively intending to export PWR. PWR rated at 325 thousand kW is being constructed in Pakistan.
India	Running Under construction Under planning Total	10 4 10 24	184 88 488 760	- In the initial stage, BWR was imported from the U.S., and CANDU from Canada. Because of nuclear testing in 1974, however, technology cannot be introduced from the U.S. and European developed countries. Heavy water reactors are designed and built from available technologies. - This country has not accepted the Non-proliferation Treaty (NPT). Full-scope security steps offered by IAEA are, therefore, not applied to this country. It has entered into the security arrangement for part of the nuclear power facilities.
Pakistan	Running Under construction Under planning Total	1 1 1 3	14 33 30 76	- This country rejected the revision of the nuclear power arrangement for security enhancement because India had carried out nuclear testing. The result is that cooperation from developed countries cannot be obtained. This country has embarked on nuclear power development by itself. - This country has not accepted the Non-proliferation Treaty (NPT). Full-scope security steps offered by IAEA are, therefore, not applied to this country. It has entered into the security arrangement for part of the nuclear power facilities.
North Korea	Running Under construction Under planning Total	2 2	200 200	- To solve problems with nuclear policies, this country decided to close and deconstruct three black-lead moderating reactors. In response to this decision, the U.S., Korea, Japan and other countries will support the nuclear industry in this country. In March 1995, the Korean Peninsula Energy Development Organization (KEDO) was established. By 2003, two standard Korean type reactors (PWR rated at one million kW) will be constructed in Shimpo City on a turnkey basis. The total construction costs will amount to 4.5 to 5 billion dollars.

TABLE 1-B: TRENDS OF NUCLEAR POWER DEVELOPMENT IN ASIAN COUNTRIES

Country		No. of reactor	10,000 kW	Trends
Indonesia	Running Under construction Under planning Total	2-3 2-3	180 180	- Site investigation into the Muria peninsula at the center of the Djawa Pulau for building nuclear power plants was carried out by New Jec, a Japanese company from 1991. In 1996, the final report was filed. - Informal plan contents are such that construction is to be started in 1998 to complete reactors rated at 1.8 million kW (900,000 x 2 or 600,000 x 3) in 2003. The final target is 7.2 million kW. - The BOO system will be adopted.
Thailand	Running Under construction Under planning Total			- The plan to start the operation of a nuclear power plant rated at 600,000 kW in 1981/82 was approved in 1974. But this plan was stopped by the discovery of a submarine natural gas field and the occurrence of the TMI accident. - In December 1995, a commission for examining the implementation of nuclear power generation was set up. The commission decided to carry out FS on this implementation.
Vietnam	Running Under construction Under planning Total			- In November 1996, the Vietnamese nuclear energy commission declared that a two-year plan (amounting to about 32 million yen) for nuclear power development focusing on FS had been started toward the implementation of nuclear power plants. - The nuclear cooperation arrangement entered into with France in 1996 targets the start of nuclear power generation around 2010.
Philippines	Running Under construction Under planning Total			- The Bataan nuclear power plant that was nearly completed in 1985 at a total cost of 2.1 billion dollars, but closed for political reasons, will be converted to a thermal gas power plant. - In May 1995, an administrative order for starting a nuclear power generation control commission was issued to examine an extensive nuclear power generation development program. An ad hoc group has been set up to investigate such issues as sites, waste control and power plant operation. Reportedly, ten candidate sites for power plants to be constructed by 2025 have been approved.

. (Sources):Kido 1997

5.   CONCLUSIONS

Some investigators have reported that an increase in global demand for energy and the corresponding augmentation of carbon dioxide emissions might be offset by the active use of renewable energy and the enhancement of energy saving. This hypothesis is, however, inapplicable to the Asian region. This report assumes the active encouragement of energy saving policies in Asian countries, as well as "unprecedented aggressive international cooperation focusing explicitly on environmental protection and international equity" (IIASA, 1995). First, the applicability of this supposition itself is questionable. Second, fully renewable energy might not be supplied even if this supposition is applicable.

To the contrary, should this supposition be inapplicable, nuclear energy could not be relied on to such an extent that the problems can be solved by nuclear power.

Many potential policies must be examined in the light of future uncertainty. In future, both renewable energy and nuclear energy must be resorted to. When nuclear energy is utilized, the use of plutonium and FBR in the Asian region must be taken into account in order to attain a continuous growth and development.

Notes:

1)   Evaluation based on the GDP is misleading. As shown in Figure 1, the evaluation based on the market rate differs significantly from the evaluation based on the PPP. The evaluation based on the PPP apparently reflects actual trends more accurately, but cannot be considered as being absolute.

2)   It is assumed in Figure 5 that the annual electric power demand in 2030 will be 1,227 TWh and costs of solar optical electric conversion will be 9.3 yen per kWh. The costs and carbon dioxide emissions show U-shaped curves against introduced solar optical electric conversion; this is because the introduction of such conversion beyond a certain limit would cause the following problems.

-       An increase in the proper reserve rate and a reduction in power generation system usage;

-       An increase in the number of power plants that use fossil fuel as a response to changes in the output from solar power plants;

-       A reduction in the number of nuclear power plants due to an increase in the number of power plants that use fossil fuel.

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NUCLEAR ENERGY AND MATERIALS IN THE 21ST CENTURY

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Abstract

The Global Nuclear Vision Project at the Los Alamos National Laboratory is examining a range of long-term nuclear energy futures as well as exploring and assessing optimal nuclear fuel-cycle and material strategies. An established global energy, economics, environmental (E^3) model has been adopted and modified with a simplified, but comprehensive and multi-regional, nuclear energy module. Consistent nuclear energy scenarios are constructed, where future demands for nuclear power are projected in price competition with other energy sources under a wide range of long-term (~2100) demographic, economic, policy, and technological drivers. A spectrum of futures is examined at two levels in a hierarchy of scenario attributes in which drivers are either external or internal to nuclear energy. The results reported examine departures from a "basis scenario" and are presented in the following order of increasing specificity: a) definition and parametric variations of the basis scenario; b) comparison of the basis scenario with other recent studies; c) parametric studies that vary upper-level hierarchical scenario attributes (external drivers); and d) variations of the lower-level scenario attributes (internal drivers). Impacts of a range of nuclear fuel-cycle scenarios are reflected back to the higher-level scenario attributes that characterize particular nuclear energy scenarios. Special attention is given to the role of nuclear materials inventories (in magnitude, location, and form) and their contribution to the long-term sustainability of nuclear energy, the future competitiveness of both conventional and advanced nuclear reactors, and proliferation risk.

1. INTRODUCTION

The goal of this study is to advance understanding of regional and long-term impacts of front-end (including reactor) and back-end nuclear fuel-cycle strategies on regional and global market shares assumed by nuclear energy. The evolution of these market shares is determined primarily by an interdependent array of economic (resource, R&D, capital, operating, and environmental costs) and policy (R&D emphases, energy structuring, proliferation concerns, security constraints, etc.) choices. These choices are influenced primarily by technological, security, and economic drivers that describe and/or influence the country or region.

Studies of the future and associated forces of change that extend much beyond a generational time horizon are subject increasingly to greater uncertainty. Impacts of these uncertainties are codified through the use of "scenario-building" techniques [1,2], where a spectrum of possible futures is quantified by means of a series of well-defined, simplified, and generally surprise-free assumptions. While an array of alternative futures contributes little to resolving an uncertain future, scenario building often allows quantitative assessment of possible eventualities while offering an improvement to the painting of a single and generally biased (either positively or pessimistically) picture of the future [2]. Furthermore, while generally constructed without specific surprising events, scenarios sensitive to critical economic drivers may offer insights into impacts of unincorporated surprises, if such events can be translated into economic terms.

The attributes of a particular scenario are expressed in terms of a hierarchical structure, at the top of which are demographic variables (population growth, age structure, workforce size and productivity, and inter-regional migrations). Population growth and the striving for improved living conditions for regional populations drive the demand for energy services, which in turn define the demand for secondary (liquids, gases, solids, and electricity) and primary (oil, gas, solids, nuclear,

solar, and hydro) energy. Most of the attributes of the nuclear energy scenarios in this study fall into the lower hierarchical echelons, which include in descending order policy, market, and technology. A framework to examine key scenario impacts uses an E^3 model [3] that has been modified to include material-inventory, economic, and nuclear-proliferation characteristics unique to nuclear energy [4].

This study addresses the following two generic questions for nuclear energy:

a) Growth: To what degree is the market share for nuclear energy determined by top-level scenario attributes (population growth, efficiency or energy intensity, environmental factors) and top-level nuclear energy costs (uranium resource, plant capital, operating)?

b) Fuel Cycle: For a given nuclear energy scenario, what are nuclear material inventory (form, quantity, region) impacts and related economic, environmental, and proliferation risks for a range of fuel-cycle options (once-through LWRs, plutonium recycle in thermal-spectrum reactors, advanced fast-spectrum plutonium burners)?

Generally, the first question relates to "external drivers," and the second question pertains to "internal questions" associated with the future of nuclear energy.

2.   APPROACH

This study of a range of possible global nuclear energy futures conforms to a hierarchy of scenario attributes that are evaluated with a modified [4] long-term E^3 model [3] that examines 13 global regions. This section summarizes the hierarchy of scenario attributes used, the model, and a "basis scenario" used as a point-of-departure for sensitivity studies.

2.1.   Scenario Hierarchy

Scenarios can be classified as both "descriptive" and/or "normative" [5]. A "descriptive" scenario evolves *via* a rule-based model without significant geopolitical, policy/institutional, economic/market, or technology changes. A "normative" scenario allows for (often interactive) modifications of these respective areas. In the context of the E^3 modeling tool, a "business-as-usual" scenario generally falls into the "descriptive" class, whereas scenarios that are perturbed relative to it exhibit more "normative" characteristics. Recent studies by the World Energy Council (WEC) [6] and by a cooperative effort between the International Institute for Applied Systems Analysis (IIASA) and the WEC [5] are contemporary examples of scenario characterization of long-term, global energy systems.

The two examples of scenario-based studies cited above are ostensibly independent of position on a given approach to providing primary energy. When used to examine possible futures from the viewpoint of a particular energy source, a scenario selection and focusing process occurs in order to emphasize specific roles and niches for the energy source considered. In the case of the IAEA Working Group #2 [7] examination of nuclear reactor and fuel-cycle strategies, three cases were identified as: "High Variant"; "Medium Variant"; and "Low Variant." This selection process is used primarily to examine a range of nuclear energy scenarios and concerns related to uranium resources, fuel-cycle facilities, nuclear-material inventories (location, quantities, and form), and spent-fuel waste. The economics that led to the particular nuclear energy demand scenarios remains relatively frozen in the assumptions of the originating [5] studies. The decoupling that results when an investigation enters the problem far down into a hierarchy of interdependent scenario attributes risks loss of opportunity to understand related tradeoffs. A recasting of the procedure used to generate the scenarios attributes embodied in the Ref. [5, 6] studies into a hierarchical format gives more visibility to this potential problem, in addition to providing both a focus and an

intercomparability to related studies. Five hierarchical levels for scenario rule/definition-making are defined and elaborated in Ref. [8].

2.2. Global Economics/Energy/Environmental (E^3) Model

2.2.1. Overview

The ERB (Edmonds, Reilly, Barns) model [3] is based on a behavioral market equilibrium that internally balances energy production and usage and is comprised of four main parts: supply, demand, energy balance, and greenhouse gas emissions. Supply and demand are determined for six primary energy categories: oil (conventional and nonconventional); gas (conventional and nonconventional); solids (coal and biomass); resource-constrained renewables (hydroelectric and geothermal); nuclear (fission, with fusion being included as a form of solar energy); and solar (excluding biomass; including solar electric, wind, tidal, ocean thermal, fusion, and advanced renewable; solar thermal is included as a form of energy conservation). The energy-balance module ensures that supply equals demand in each global region, with electrical energy being generated and used only within a given global region. Energy and economic (market-clearing) balances are performed for 13 global regions at nine 15-year steps covering the period from 1975 to 2095. Energy balance across regions is established by a set of rules [3] for choosing the respective prices and price scalings that are required for supply to equal demand in each energy-service group for each fuel.

The demand for energy services in each global region is determined by: the cost of providing these services; level of income (~GNP); and regional population and top-level demographics. Energy services are fueled by an array of four secondary fuels (liquids, gases, solids, and electricity). The mix of these secondary fuels used to provide a given energy service is determined by a cost-based market-share algorithm [3], as is the demand for fuels used to produce electricity and the share of oil and gas provided by transformation of coal and biomass. The tracking of primary energy to secondary energy sources to energy services transformation is modeled using a Leontief-type formulation. The energy demand module also maintains a set of energy flow accounts. The energy supply module estimates: a) the supplies for all regions and fossil fuel forms that forms the basis for (iterating) world (fossil-fuel) prices; b) the cumulative usage; c) and the cost of recovery (including environmental costs) at one of five resource grades. Energy supplies are disaggregated into two categories: renewable (hydro, solar, biomass, and nuclear breeder) and non-renewable (conventional and unconventional oil, natural gas, coal, and non-breeding nuclear). A given resource is active and able to contribute to demand only if the primary energy price delivered to the energy supply module exceeds the production cost, and if the resource has not been exhausted.

2.2.2. Nuclear Model

The nuclear model developed and operated "under" the ERB model [9] performs three primary functions:

a) It determines a "top-level" cost estimate in terms of a cost of electricity, COE(mill/kWeh), that is reformed into the Leontief coefficients used in ERB to estimate market shares.

b) It tracks the flow of key nuclear materials throughout the nuclear fuel cycle (natural uranium, low-enriched uranium, plutonium, and spent fuel) for use in subsequent nuclear materials and proliferation-risk assessments.

c) It performs a multi-attribute utility analysis of proliferation risk [10–12] from the civilian fuel cycle.

The uranium resource model originally used in ERB [3], for purposes of the present study, has been replaced with that of Ref. [13], as interpreted in Ref. [14].

The nuclear model is based only on the uranium/plutonium cycle, as utilized in each global region at each time interval by an economically determined mix of light water reactors (LWR) and breeder reactor systems. The LWRs in a given global region operate along an exogenously enforced trajectory of MOX-recycle core fractions, as is described in Section 3.2.2.2. The breeder system, if economics and technology diffusion time constraints allow, is introduced with a preassigned breeding ratio. In the present version of the model, plutonium is assumed to flow freely between global regions as needed, where deficits in LWR-usable material arising in some regions are assumed to be corrected by flows from regions with excess (LWR-usable) plutonium.

Costing of nuclear energy is based on a top-level, highly aggregated algorithm [9] that accounts for annual capital charges, annual plant operating and maintenance charges, and annual charges related directly to the nuclear fuel cycle. The component of the COE related to the plant capital costs is expressed in terms of a fixed charge rate and a unit total cost, UTC($/We), while annual operating charges are expressed as a fraction of the total capital cost of the power plant. Differences in COE between LWRs and breeders are reflected primarily in differences in the respective unit total cost values and that part of the COE related to the fuel cycle [9]. For each global region and time interval, the COE-minimizing fraction of nuclear energy delivered by LWRs (for a given MOX recycle fraction) is determined, and an LWR-breeder reactor composite price is returned to the ERB demand module for evaluation of the respective market share for that particular region and (iterated) market-clearing world fossil-fuel price.

The nuclear fuel cycle is described in terms of the following sequence of processes: mining and milling of uranium; conversion of uranium oxide to the volatile fluoride; isotopic enrichment; fuel fabrication; fissioning in reactor; spent fuel cooling and storage; reprocessing; and repository storage directly as spent fuel or as separated fission products and minor actinides. The simplified species-resolved mass balances, based on input-output analysis [15], are used to model regional and temporal material flows. Unit and operating costs are applied to each of these processes, from which a fuel-cycle cost for the entire system (LWRs plus breeder reactors) is determined. Plutonium flows and accumulations are monitored for each global region as a function of time, with reactor plutonium, separated plutonium in reprocessing and fuel fabrication, and accumulated plutonium in spent fuel (differentiated into LWR-recyclable or non-recyclable forms) being the four major categories tracked.

2.2.3. Basis Scenario

The primary function of the "basis scenario" is to provide a point-of-departure to which shifts from upper-level or lower-level hierarchical variations can be referenced. The basis scenario reflects a "most probable future," albeit uncertainties are great and "projections" per se are not intended. Major forces behind total primary energy demand are population growth, workforce makeup and productivity as it drives GNP growth, and the efficiency with which primary energy is converted to secondary energy and ultimately to the provision of energy services. These top-level scenario attributes are inter-related in a way that is not captured by most long-term E^3 models. While these top-level scenario attributes strongly impact energy demand, that part of the demand potentially served by nuclear energy is determined in competition with alternative sources through economic, environmental, and policy choices made further down the hierarchical chain described above and elaborated in Ref. [8]. The adaptation of a generalized scenario attribute hierarchy to the problem at hand is illustrated in Table I, which serves as a "roadmap" for this study.

The top-level scenario attributes that characterize the basis scenario use the data base (with some modification) from an application of the ERB model to understanding the economics of carbon-dioxide emission control [3,16-18]. The population data base originally used in ERB was shifted upward (by ~10%, depending on the region) to reflect recent U.N. projections [5, 6]. The GNP projections begin with base-year (1975) values, and then scale subsequent years according to population growths, workforce productivity increases, and energy service prices. The exogenously

46

TABLE I SUMMARY OF ERB UPPER-LEVEL (EXTERNALLY DRIVEN) SCENARIO ATTRIBUTES LEADING TO LOW-TO-HIGH NUCLEAR ENERGY GROWTH RATES

Attribute Identifier[e]	Impact on NE Growth	Population (billions)	GNP Productivity Multiplier	Energy Intensity (%/a)[c]	Carbon Tax ($/tonne/15 yr)	LWR Unit Capital Cost UTC ($/We)[b]	LWR Pu Recycle f_{MOX}[f]	LMR Unit Capital Cost UTC_{LMR}/UTC_{LWR}[d]	Uranium Resource[a]
BASE	Medium	11.7	1.0	1.0	0.0	2.0 → 2.4	0.0	1.5	KR
POP									
• POPL	Medium	10.0	1.0	1.0	0.0	2.0 → 2.4	0.0	1.5	KR
• POPH	Medium	13.8	1.0	1.0	0.0	2.0 → 2.4	0.0	1.5	KR
GNP									
• GNPL	Low	11.7	0.8	1.0	0.0	2.0 → 2.4	0.0	1.5	KR
• GNPH	High	11.7	1.2	1.0	0.0	2.0 → 2.4	0.0	1.5	KR
EI									
• EIL	High	11.7	1.0	0.0→1.0	0.0	2.0 → 2.4	0.0	1.5	KR
• EIH	Low	11.7	1.0	1.0→2.0	0.0	2.0 → 2.4	0.0	1.5	KR
TAX	High	11.7	1.0	1.0	20. → 40.	2.0 → 2.4	0.0	1.5	KR
UTC[g]									
• UTCL	High	11.7	1.0	1.0	0.0	2.0 → (1.5,2.0)	0.0	1.5	KR
• UTCH	Low	11.7	1.0	1.0	0.0	2.0 → (3.0,4.0)	0.0	1.5	KR
RES[g]	Medium	11.7	1.0	1.0	0.0	2.0 → 2.4	0.0	1.5	CR → TR

(a) CR = Conventional Resources; KR = Known Resources; TR = Total Resource [13, 14].

(b) range indicates time evolution, with final (higher or lower) values achieved by ~ 2020.

(c) values given indicate annual reduction in secondary energy required to satisfy a given end-use requirement.

(d) varied only as a lower-level (internal driven) scenario attribute.

(e) variations: BASE = base case; POP = population; L,H = low, high; GNP = Gross National (World) Product; EI = energy intensity; NE = nuclear energy; UTC = unit total cost; RES = uranium resources.

(f) varied only as a lower-level (internal driven) scenario attribute.

(g) "baseline" upper-level scenario attribute in this study.

determined productivity increases were left unaltered from the original ERB data base. Energy intensity is specified through improvements in efficiencies that relate energy service demands to the amounts of secondary energy needed to meet these demands. The ~1%/year decrease in the ratio of energy service to secondary energy is used in this study to define the basis scenario. The relationship between cost and fossil fuels grade was used without modification in this study, but the uranium resource cost *versus* grade relationship given in Ref. [13] replaces that originally used in ERB [3]. Taxes and tariffs, as reported in the ERB model, remain unchanged. The main taxation variation was that applied at the consumption level to stem atmospheric carbon emissions; for the basis scenario, the carbon tax is zero. Reference [8] provides key nuclear energy parameters used to perform nuclear materials balances and to determine market shares for the basis scenario and subsequent scenario variations.

To simplify data displays and to facilitate comparisons with other studies [5–7], the 13 regions have been aggregated into three macro-regions, as was done in Ref. [5]: industrialized countries (US, Canada, OECD-Europe, OECD-Pacific); reforming economies (eastern Europe, former Soviet Union); and developing countries (China, southeast Asia, India, Latin America, northern and southern Africa, Middle East). Comparisons of total primary energy and total nuclear energy projections with WEC results [5, 6] via the IAEA study [7] are reported in Figs. 1a and 1b. Aggregated growth rates of GNP, primary energy, and energy intensity also compare favorably [8].
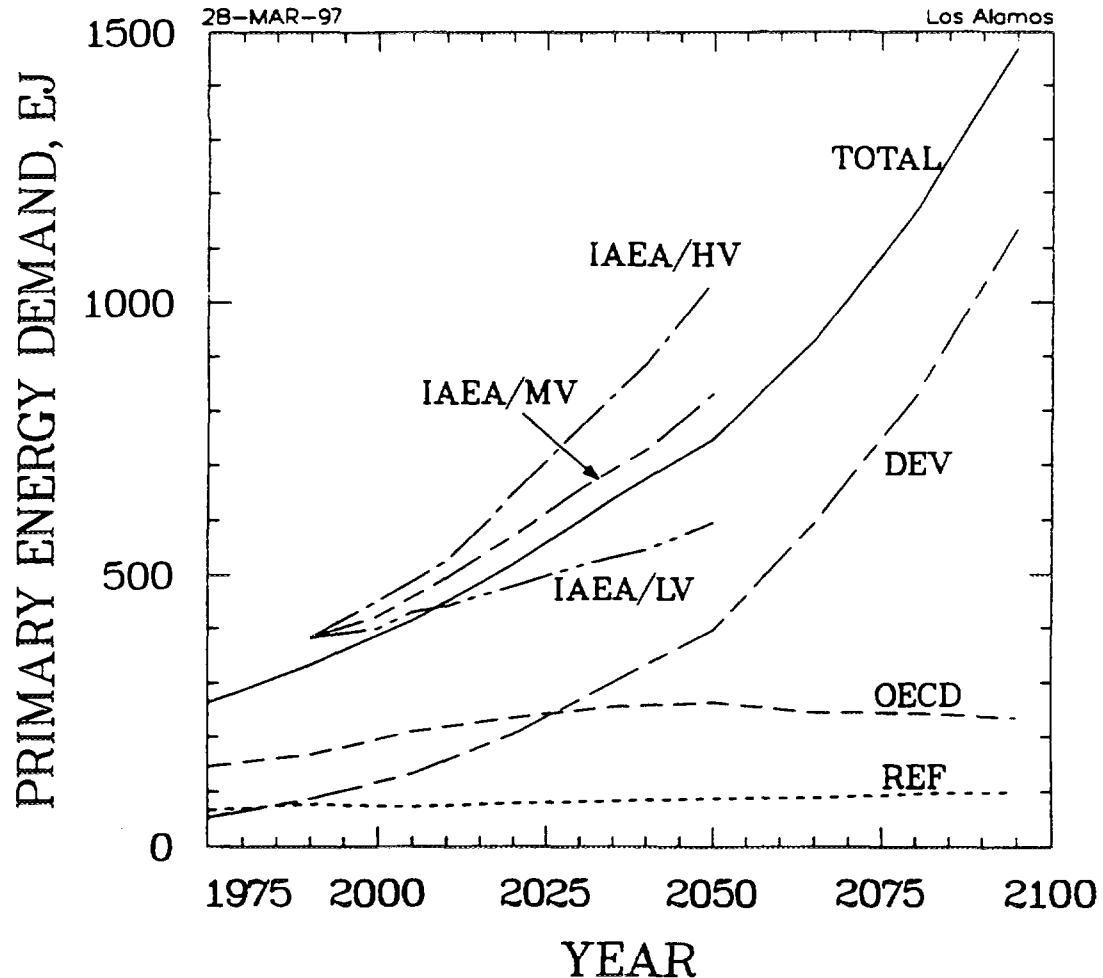
FIG. 1a.   Evolution of aggregated total primary energy for the basis scenario; a comparison is made with the Ref. [7] high (HV), medium (MV), and low (LV) variants, as adopted from the WEC/IIASA [5] study.
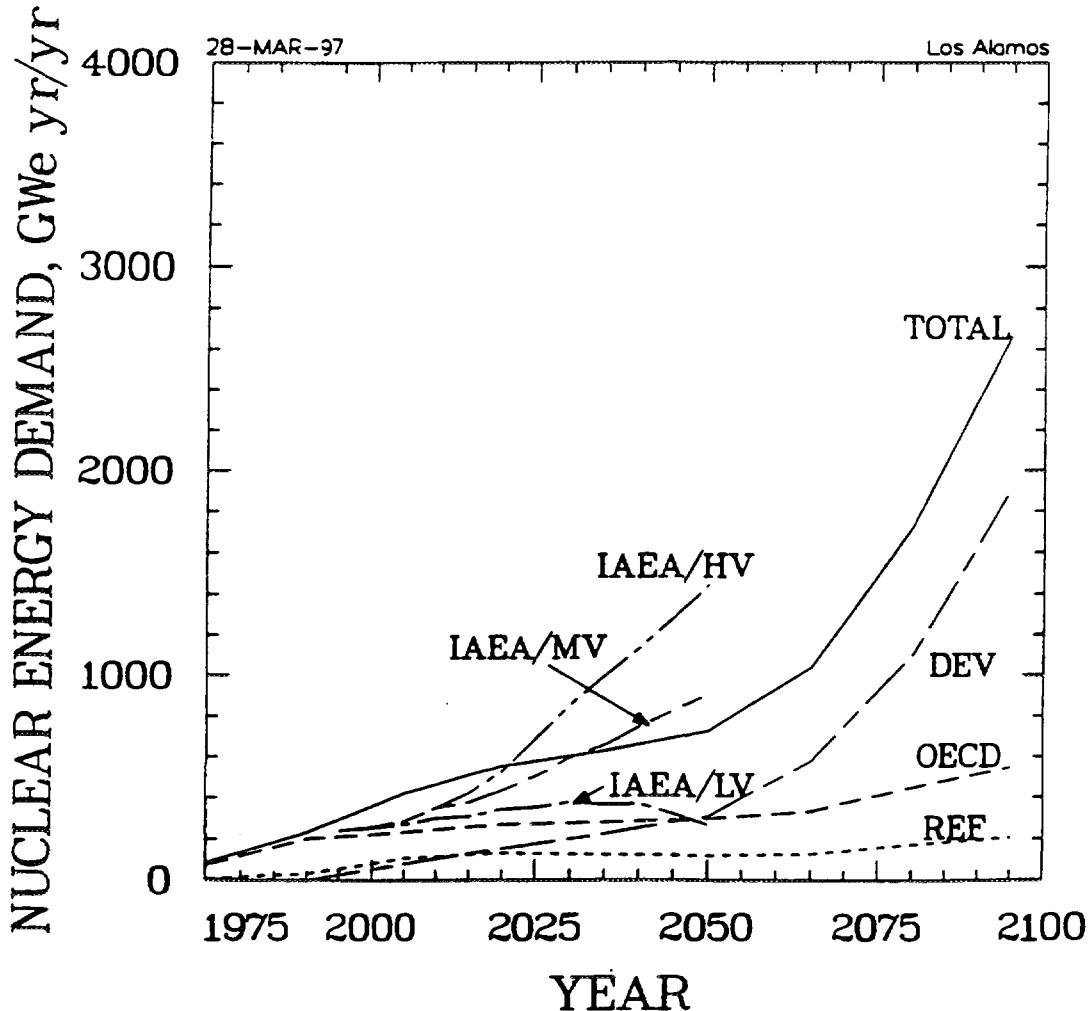
FIG. 1b. *Aggregated nuclear energy growth rates for the basis scenario; a comparison is made with the Ref. [7] high (HV), medium (MV), and low (LV) variants.*

3. RESULTS

The results presented in this section are based on departures from the basis scenario and are divided into two broad categories: external drivers (variations in upper-level parts of the scenario attribute hierarchy that are considered "predetermined conditions" [1]); and internal drivers (variations in attributes that reside at the lower rungs of that hierarchy and are characterized as "critical uncertainties" [1]). Departures from the basis scenario nuclear energy demand are caused by changes in these upper-level attributes. Sensitivities of demand to these upper-level attributes are first reported. The "departure" scenarios that result from variations in these external drivers provide the basis for a range of nuclear energy demand variants that parallel those reported in Ref. [7]. The impacts of drivers that are internal to nuclear energy (scenario attributes that are lower in the scenario-attribute hierarchy) on the choice of optimal nuclear fuel-cycle strategies and the relationship of these choices to the external drivers are examined for both the basis scenario and for a range of departure scenarios.

3.1. Upper-Level Hierarchial Variations: Impacts of External Drivers

The five external drivers (population, GNP, energy intensity, taxes, and nuclear economics) are combined with the top-level economic parameters [capital and (uranium) resource costs] to define

49

the main "external drivers" that are varied to explore possible nuclear energy demand scenarios. All upper-hierarchical variations are single-point perturbations about the basis scenario, which is characterized by a once-through LWR fuel cycle.

3.1.1. Population

The basis scenario and most of the related departure scenarios follow the U.N. population project that predicts nearly 12 billion persons on earth by the year 2100. Adjusting [8] regional asymptotic population levels used to model regional population growth in the modified model gives ~± 17% variations in world populations in 2100 relative to the U.N. projections. These single-point population variation were made without adjustments to the base (1975) GNP used in the ERB model. Figure 2 shows results of population variations.

3.1.2. Workforce Productivity

The ERB model adjusts a base regional GNP in time for: population increase; an aggregated price for energy services using region-dependent price elasticities; and an increase in workforce productivity, which is expressed as a region- and time-dependent rate of annual productivity enhancement. The impact of region-independent increases and decreases in productivity by ~± 20% on GNP was examined. This productivity reflects evolving workforce percentage (of total
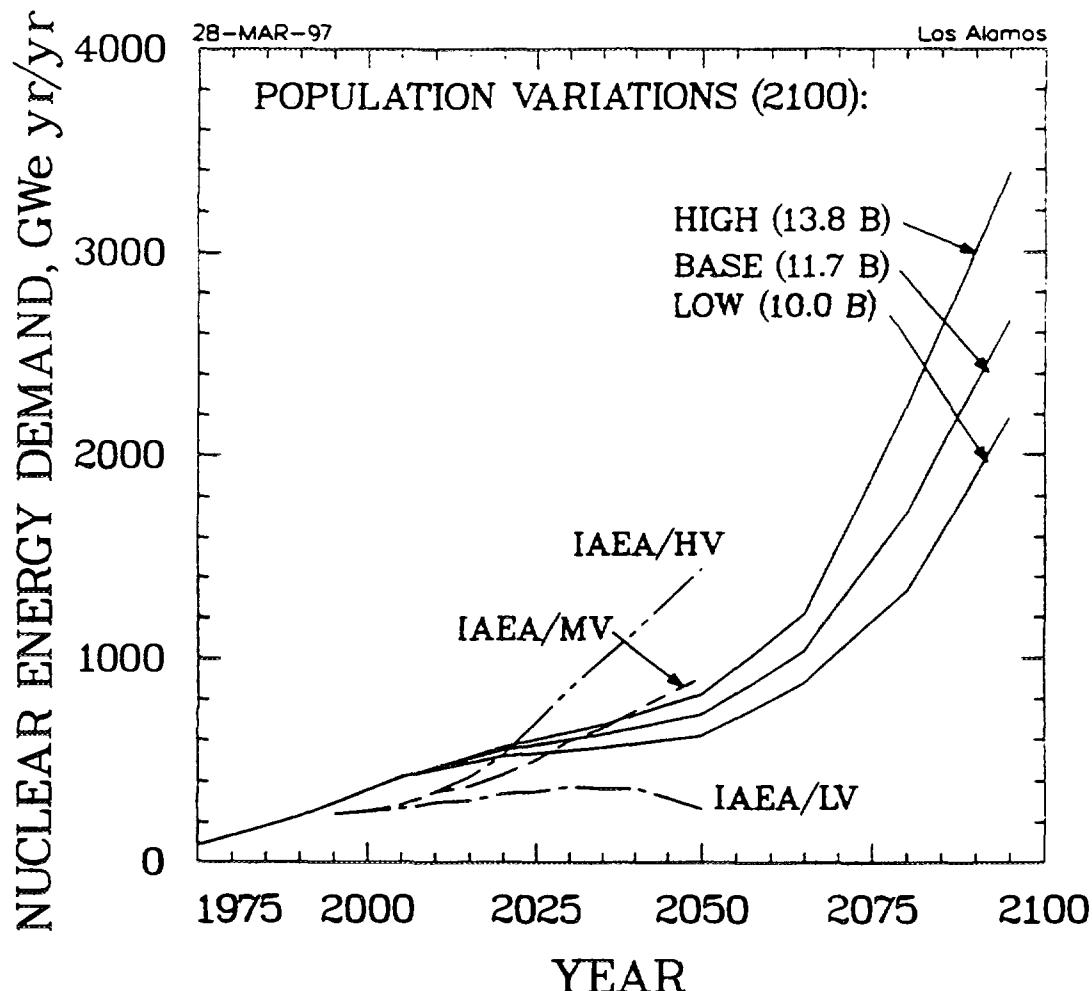
FIG. 2.   Impact of population variations on nuclear energy demand; comparison with Ref.[7] scenarios is given.

50

population), age distribution, and skill levels, all of which show strong regional dependencies. The impacts of these GNP variations on nuclear energy demand are shown in Fig. 3. These impacts on energy demand, for the income elasticities used in the ERB model, are much greater than that for single-point population variations alone.

3.1.3. Energy Intensity (End-Use Efficiency)

The ERB model varies (primary- or secondary-) energy intensity indirectly through a technology improvement rate that relates an ever decreasing secondary-energy requirement needed to satisfy a given demand for energy service. The basis scenario uses a regionally dependent technology improvement rate of ~1.0%/year, which is unchanged from that in the original ERB data base. Generally, the decrease in the primary-to-secondary energy conversion efficiency *versus* time is a result of regional populations demanding higher forms of energy (liquids and electricity) to meet the energy service demands of a growing population that experiences more wealth. The impacts of a range of technology improvement rates on the demand for nuclear energy is shown in comparison to the Ref. [7] demand scenarios in Fig. 4. A technology improvement rate as high as ~1.5-2.0%/year closely tracks the "ecologically driven" low-variant scenario of Ref. [7], whereas the technology improvement rate must fall to ~0.5%/year to reproduce the high-variant case reported in Ref. [7].
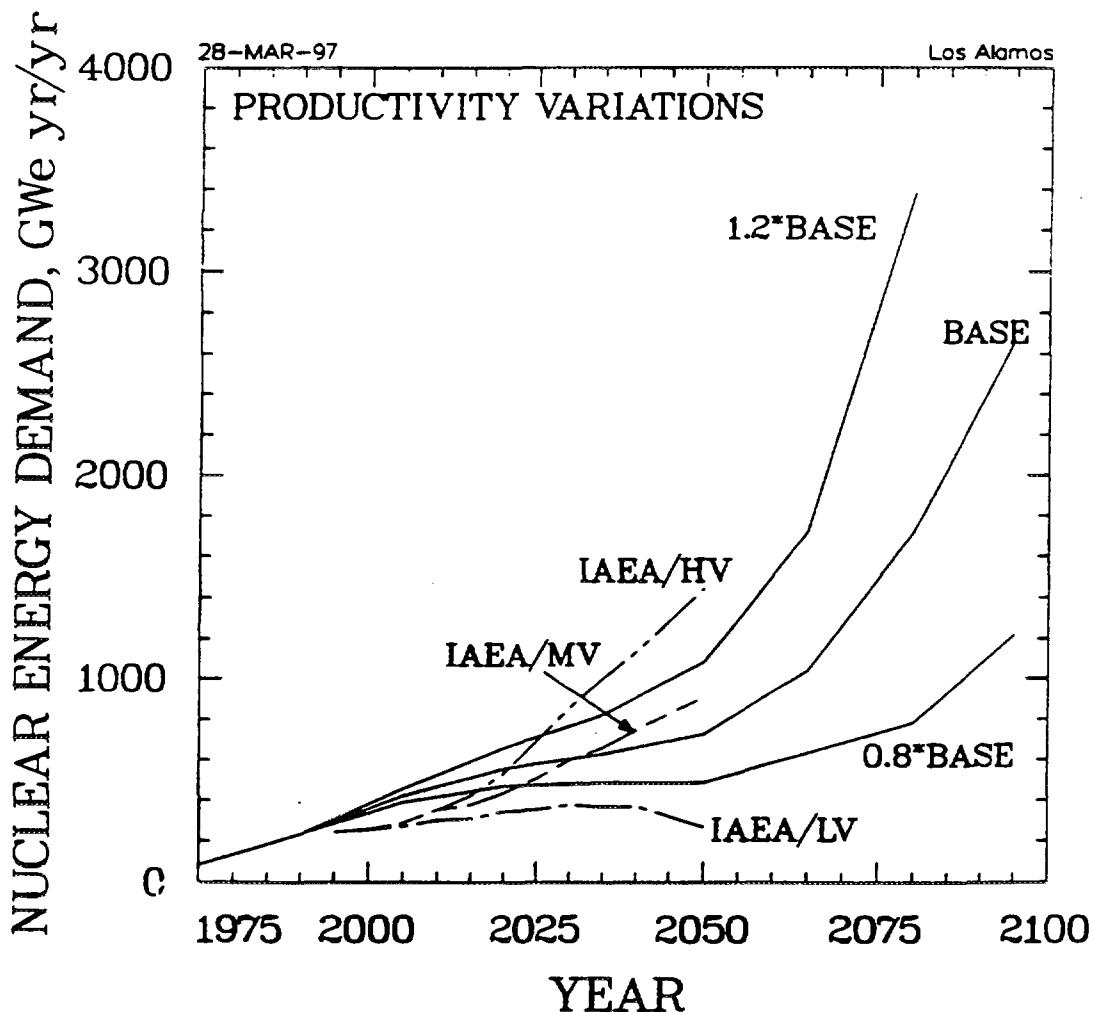
FIG. 3.   Impact of workforce productivity (GNP) on total nuclear energy demand; comparison with Ref.[7] is given.
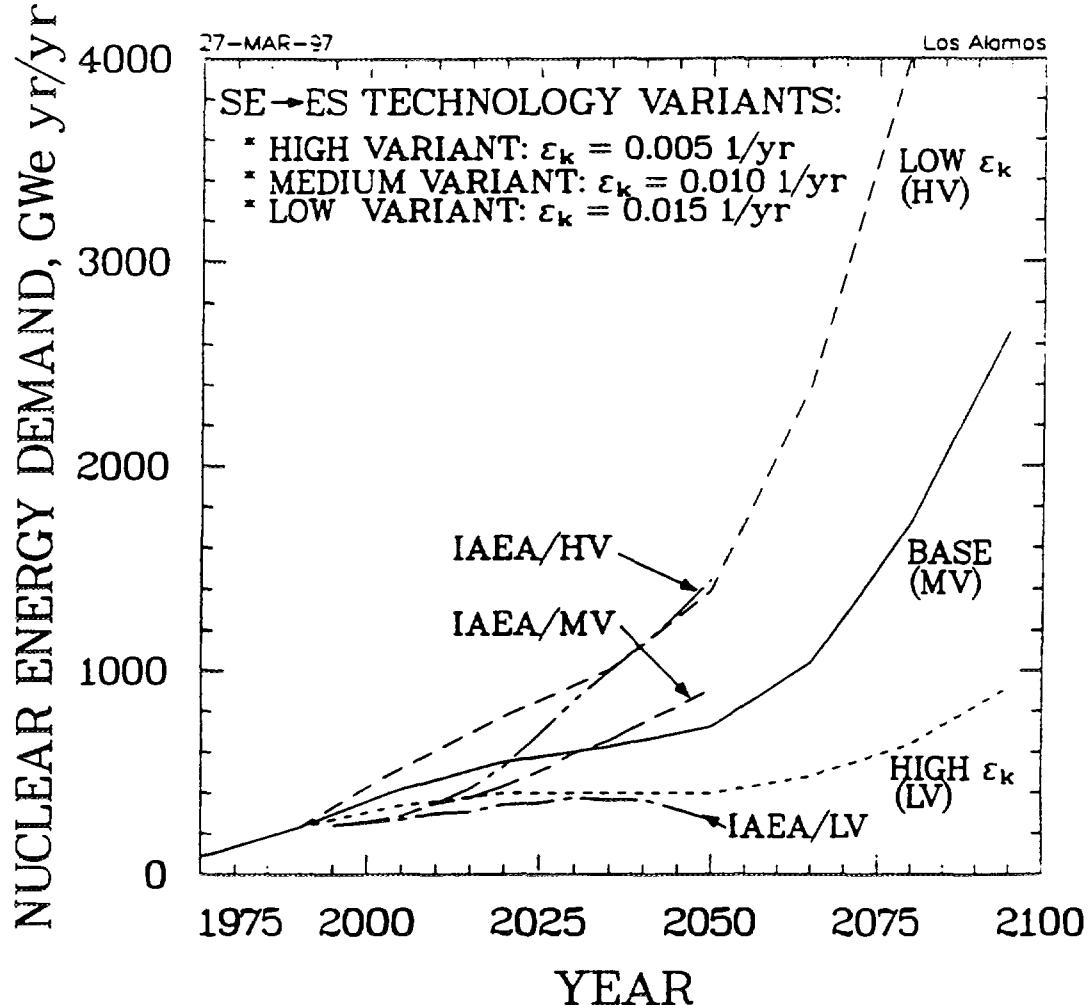
FIG. 4. *Impact of energy-service technology improvement (ε_k) on nuclear energy demand, and comparison with Ref. [7]; the ε_k = 0.005, 0.01, and 0.015 1/yr cases[8] create high, medium (basis-scenario) and low variants on nuclear energy demand.*

3.1.4. Carbon Tax

The imposition of a carbon tax has the effect of increasing the cost of fossil fuels (particularly coal), decreasing total energy use and GNP (somewhat), while increasing the market share for reduced- or zero-carbon energy sources. The impact of applying a strong carbon tax rate (40 $/tonneC/15yr) on the demand for nuclear energy is shown on Fig. 5. This carbon tax rate stabilizes total carbon emission to values associated with the year of implementation [8]. Halving this rate produces global carbon emissions that are significantly higher (> 50%), but these emissions are a factor of two lower than for the basis scenario of no tax. For these and the basis scenario, biomass is priced high and does not become a major contributor to the primary energy demand, although the impacts of reduced biomass costs have been reported [17].

3.1.5. Nuclear Economics

Although the details of nuclear energy cost logically should be treated as an "internal driver," for the purposes of this study and the focus given to nuclear fuel-cycle internal drivers, the capital and resource costs associated with nuclear energy are included as a "borderline external driver."
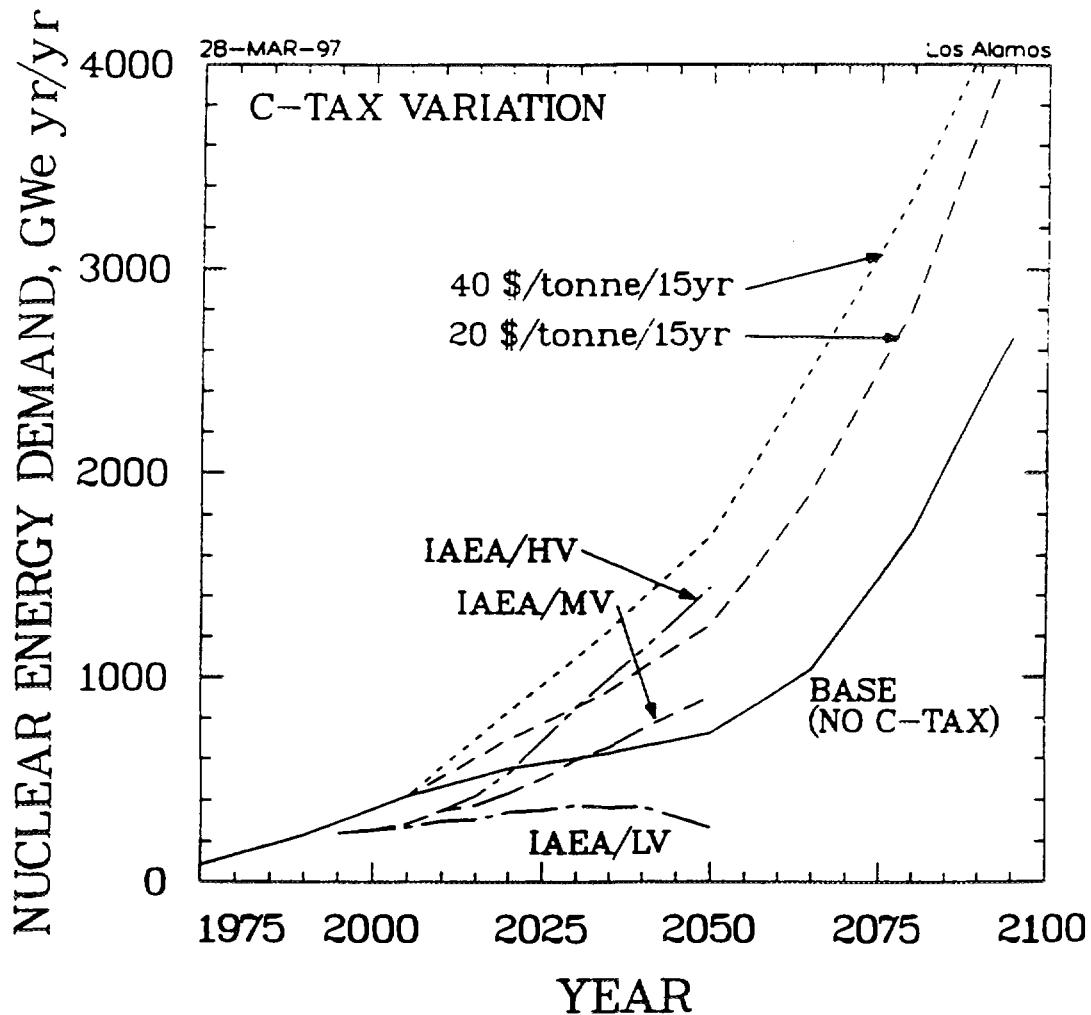
FIG. 5.   Impact of carbon taxes on nuclear energy demand; comparison with Ref.[7] is given.

3.1.5.1. Capital Cost.

For the uranium resource model used and the unit costs associated with the once-through LWR fuel cycle [8], the capital cost is the main component of the COE for nuclear power and, hence, the main determinant of market share returned by the ERB model. The capital cost is embodied in a single variable - the unit total cost, UTC($/We). The basis scenario adjusted this cost for 1975 and 1990 for relevant regions so that the model returned an annual nuclear energy generation that approximated historical values. These unit cost values typically are in the range 1.5-2.0 $/We. The basis scenario then increased this cost over the period 2005-2095 to achieve an asymptote of 2.4 $/We. The impacts of increasing or decreasing this asymptote to 3.0 or 2.0 $/We, respectively, are shown in Fig. 6. All regions were treated equally for times greater than 2005. The impact of these unit cost variations on atmospheric carbon emissions is small [8] compared to the imposition of carbon taxes. Generally carbon taxation creates a favorable environment for nuclear energy growth with reductions in GHG emissions, but the cost-driven increase or decrease in nuclear energy demand alone has little impact on GHG emissions.

3.1.5.2. Uranium Resource

The relationship between uranium resource grade, resource amount, and cost [13, 14] is used to provide the scaling of unit cost with accumulated uranium use. The basis scenario assumes that
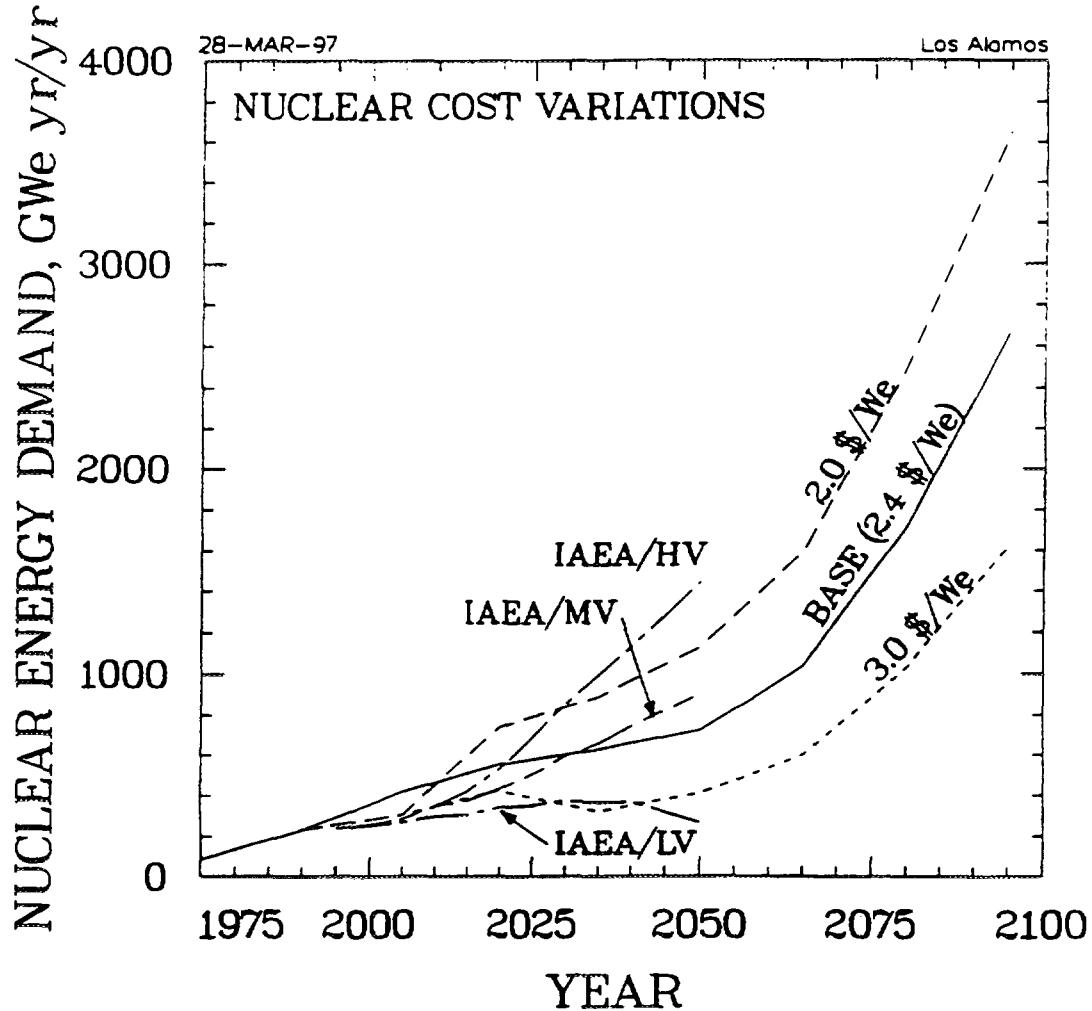
FIG. 6.   *Impact of nuclear energy capital costs on nuclear energy demand; comparison with Ref.[7] is given.*

the Known Resources category [13] describes reality. The weight fraction of ^{235}U in tailings is determined by the minimum cost conditions [15, 19] for the relative values of mined/milled uranium unit cost and a chosen unit cost of enrichment [8]. A minimum price of 100 $/kgU for mined/milled uranium is enforced for all resource categories, and the optimum-cost tailings fraction (normally 0.23 weight percent, but decreasing for more conservative resource assumptions [8]) is used in all cases.

The dependence of uranium usage, unit cost, and optimal enrichment on time and uranium resource assumption is described in Ref. [8]. For both Known Resource and the Total Resource categories [13, 14], uranium costs remain at the threshold price for the basis scenario nuclear energy demand, although a departure from the threshold price beyond ~ 2080 for the basis scenario (once-through LWR, Known Resource) occurs. The Conventional Resource category shows an increase in uranium prices after the year 2050 for the basis scenario nuclear energy demand, with these increased uranium prices resulting in a decreased nuclear energy demand and reduced uranium consumption. These decreases are small and occur only after 2070. Earlier studies using the ERB model [4] were based on a resource depletion model [15] even more conservative than the Conventional Resource case; higher uranium prices resulted in higher overall fuel cycle costs earlier than those found here. The introduction of a carbon tax and the resulting increase in nuclear energy demand also increases the rate of uranium resource depletion and the unit cost of uranium fuel.

3.2. Lower-Level Hierarchical Variations: Impacts of Internal Drivers

This section examines strategies and technologies for back-end material management. The resource and economic conditions necessary for the introduction of the commercial-power breeder reactors, however, are reported first.

3.2.1. Breeder Reactors

As described in Ref. [9], the cost of nuclear energy used to generate regional market shares is determined by means of an optimization procedure applied at each of the nine 15-year time intervals. This procedure compares a full range of LWR-breeder reactor mixes on a COE basis to determine the reactor makeup (LWRs and breeder reactors) for a given region and time that would minimize the overall cost of nuclear energy used to estimate market shares. For low uranium resource depletion (low costs), higher breeder capital and fuel-cycle costs, and without imposing added external costs for LWR-derivative plutonium and waste accumulations, addition of breeders to the nuclear energy mix generally increases the cost of nuclear energy [8]. For scenario attributes where breeder introduction reduces the overall cost of nuclear energy, the regional introduction of advanced breeder reactors is limited by a technology diffusion time [20].

A breeder reactor having a fifty percent higher direct cost relative to a LWR would not be economically competitive under the basis scenario demand (uranium cost scaling based on the Known Resource category). Within the model, three scenario attributes were modified to stimulate the introduction of breeder reactors:

a) use of the more conservative Conventional Resources uranium resource model;

b) reduce the capital cost of the breeder reactors in relationship to LWRs; and

c) stimulate overall demand for nuclear energy and demand for uranium by imposing carbon taxes or reducing overall costs of nuclear energy.

Time dependencies of economic- and technology-driven breeder introduction profiles on a range of favorable scenario attributes are illustrated in Fig. 7, where the fraction of all LWR-generated nuclear energy is determined under the assumption that all factors determining the time-dependence of the fraction of LWRs are independent of region. All cases examined used: a) the once-through LWR basis scenario; and b) scaled uranium cost according to the more conservative Conventional Resource scenario. The latter attribute is essential for breeder reactor introduction under realistic variations of the other scenario attributes listed above. With these assumptions, economic entry of the breeder occurs within the ~2100 time frame of this computation only for breeder cost increments (relative to LWRs) of ²10 percent. Increasing the demand for nuclear energy (and uranium resources under the Conventional Resource scenario) by imposing a strong worldwide carbon tax both decreases the breeder introduction date and/or increases the cost threshold (Cases B and C, Fig. 7). Increasing the share fraction of nuclear energy by decreasing overall cost (Section 3.1.5.1) has a similar impact on breeder introduction, as does the imposition of a carbon tax, with both cases pertaining to breeder capital cost increments of 10 percent over that for LWRs. Finally, re-imposing the basis scenario resource attribute of Known Resource scaling, the conditions of low overall nuclear costs, and a breeder cost increment of 10 percent (Case D) pushes breeder introduction to beyond the ~2100 time frame of this computation.

The main plutonium-inventory impact of scenario attributes that allows the economic introduction of breeders is the plutonium accumulated from previous LWR operations being transferred to the displacing breeder reactors. However, full global implementation of breeders under the Case D scenario is insufficient to meet new-reactor inventory demand. Increasing the breeding ratio from unity to 1.2-1.3 has little impact on the plutonium deficit; the demand by new breeders exceeds any breeding capacity on the time scales being considered.

CASE	$f_{UTC}^{(a)}$	C-TAX	UTC$_{LWR}$
A	0.1	NO	BASE
B	0.3	YES	BASE
C	0.1	YES	BASE
D	0.1	NO	LOW

note: left curves economic
right curves technology

$^{(a)}f_{UTC} = UTC_{LMR}/UTC_{LWR}$
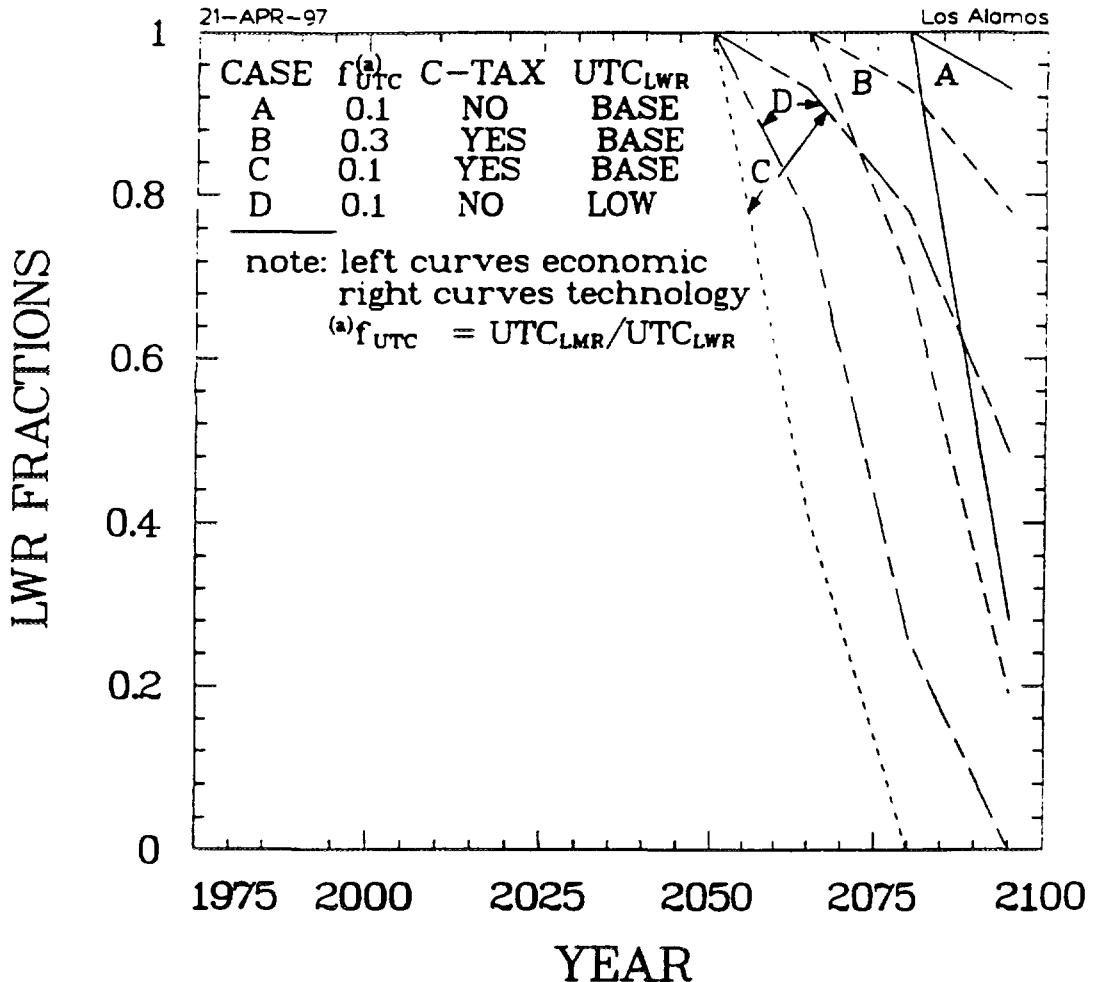
FIG. 7.   Time dependence of economics- and technology-driven introduction of LMRs on a range of favorable scenario attributes, where f_{LWR} is the fraction of all nuclear energy generated from LWRs under the assumption of a homogeneous world. The conservative Conventional Resource uranium resource [13] and associated costing scaling [8] was used for all four cases to enhance LMR introduction.

3.2.2. Once-through LWRs

Except for the generation, flows, and inventories of nuclear materials, the once-through LWR scenario has been described essentially by the basis scenario. The majority of the plutonium for the basis scenario resides in spent-fuel form; inventories of separated (in reprocessing and MOX fuel fabrication) and fully recycled plutonium are nil. The breakout of the total plutonium inventory curve on a macroregional basis (OECD, REF, and DEV) is given in Fig. 8. Most notable from this figure is the shift in plutonium accumulations towards the developing regions, in spite of the large "head start" for the OECD countries. While the global distribution of total plutonium (mainly in spent-fuel form) appears to move towards global uniformity [8], plutonium contained in reactors initially becomes more uniform on a regional basis, but the large growth in developing regions skews the global distribution of reactor plutonium at later times.

3.2.3. Plutonium Recycle in Light-Water Reactors

For each global region, the LWR recycle model forces the volume fraction of the core that is operated on MOX to follow a time dependent trajectory resulting in a globally averaged MOX fraction for all LWRs. The model does not make the choice of MOX fraction on economic grounds,
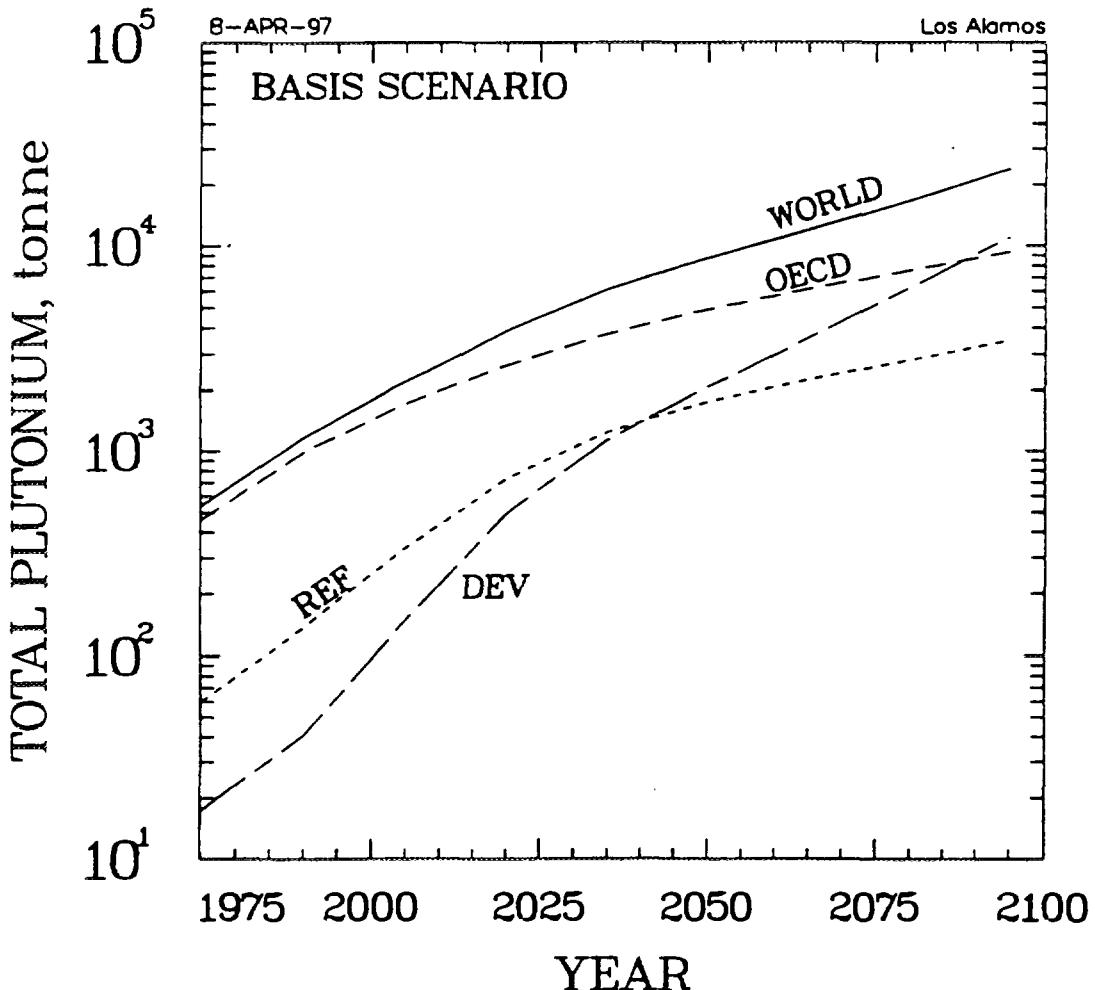
FIG. 8. *Macro-region breakout of total accumulated plutonium for the basis scenario (once-through LWRs, Known Resources [13]).*

nor does it constrain the introduction of MOX systems to account for possible regional deficiencies in plutonium supply that might arise. The function [8] used to drive the MOX fraction is characterized by the initial MOX core fraction, the final (asymptotic) MOX core fraction, the time at which the MOX trajectory is initiated, and a nominal doubling time used to determine the rate at which the MOX core fraction approaches the asymptotic value; all of these MOX characteristics are dependent on global region, although most results reported herein pertain to a uniform world in this regard.

A present model limitation is the absence of an inter-regional plutonium allocation algorithm. For a given MOX fraction (uniformly applied to all global regions) and evolving demand for nuclear power, the amount of LWR- recyclable (^{2} 3 recycles) spent-fuel plutonium available in a particular region needed to supply new MOX fuel may fall below zero. For regions where such inventories are insufficient to meet local demand, a negative inventory is recorded that reflects plutonium being used in regional reactors that originated from outside that region. Presently, the tracking of regional total plutonium inventories includes only positive entries under the presumption that negative values of accumulated plutonium would be met from regions with surpluses through a set of allocation or "market" rules. Whenever regional totals are presented, they reflect an inflation related to these unresolved "contributions" from regions with surpluses in order to resolve deficits in other regions. These deficits are resolved on a global basis, however, when total plutonium inventories are reported. In essence, regions that operate with negative inventories are allowed to

push forward any market-driven growth in nuclear energy and increased use of MOX cores, but the required subtractions from regions with positive available plutonium inventories are made only at the global level. An alternative approach would limit the degree to which MOX is used in a given region to the regional inventories and/or production rates.

The evolution of the global plutonium inventories according to form is shown in Fig. 9 for a MOX core fraction of 0.3 (implementation begins in 2005 and is assumed to saturate at 0.3 around 2030). This figure indicates first a depletion in world values for available (LWR-recyclable) plutonium, followed by a recovery. Comparisons are given with the once-through and recycle (30 percent MOX core) cases reported in Ref. [7]. The buildup in plutonium that has been fully recycled and in separated (in reprocessing and MOX fuel fabrication) plutonium inventories is noted. The nominal basis LWR-based nuclear energy scenario coupled with choice of MOX fraction leads to a continued and growing inventory of multiple-recycled plutonium that is not usable in thermal LWRs. Until the impact of China becomes strong in the basis scenario (around 2040 - 2050), most of this multiple-recycled plutonium resides in OECD countries.
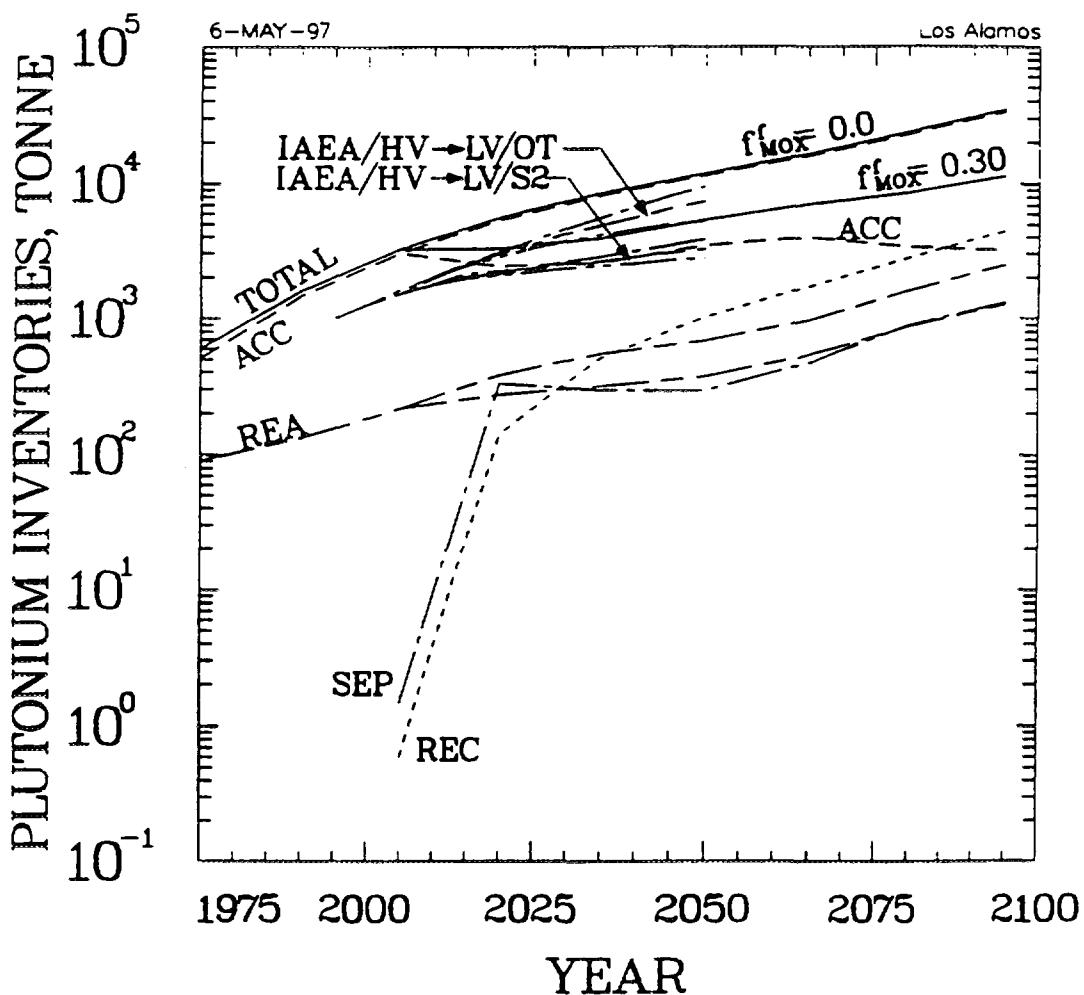
FIG. 9.   Time dependence of global plutonium inventories by form for a MOX core (volume) fraction of 0.30 beginning in ~ 2005 and taking 25 years to reach this asymptote. ACC = plutonium accumulated in spent fuel form that can undergo recycle back to the LWR; REC = plutonium that has experienced the maximum

(N = 3) recycles; REA = average plutonium inventoried in reactors; SEP = separated plutonium in MOX fuel fabrication and chemical processing;
TOTAL = ACC + REC + REA + SEP.

These results treat the world uniformly concerning level of plutonium recycling in each region. In reality, the trajectories occurring for plutonium recycle will depend on regional details, as determined by technical motivation and capability, economic status, and state of international controls/sanctions. Under some conditions [8] (e.g., higher MOX core volume fractions, higher burnups, higher plutonium loaded into MOX, etc.), a moderate imbalance can a result in the world accumulated inventories becoming slightly negative for short periods. Temporal and regional tailoring of the MOX fractions can flatten global accumulations of LWR-recyclable plutonium close to zero, which in ideal circumstances would be the role of the "market." Finally, the long-term impact of plutonium use in LWRs on the uranium resource and cost is moderate for the basis scenario, generally being in the range of 25 percent for a MOX core fraction of 30 percent around the year 2075. Furthermore, the increased cost of reprocessing and MOX-fuel fabrication for the basis scenario increases cost somewhat, which translates approximately into a 10 per cent reduction in global demand in 2050 [8].

3.2.4 Fast-Spectrum Plutonium Burners

The use of fast-spectrum burners (FSBs) (see Ref. [21] for recent design studies) to fission more completely all isotopes of plutonium and the minor actinides (e.g., neptunium, americium, and curium) is examined here. The results of Section 3.2.1. indicated that little or no penetration of breeder reactors (on economic and resource availability grounds) might be expected until the latter half of the 21st century. However, FSB systems might be used in conjunction with LWRs (operating under either once-through or multiple-recycle conditions) to create alternative approaches for dealing with the plutonium inventories accumulating from LWRs. The use of FSB, like the LMR/IFR [21, 22] or accelerator-based (ATW) [23, 24] systems, is expected to be pursued at some economic penalty, in that these systems may have capital and operating costs that would require the sale of electrical power at higher COEs than from LWRs that accumulate plutonium at low to moderate charges. In conducting a preliminary inquiry into potential roles of FSBs, the following preliminary questions were addressed:

a) To what extent must the COE be incremented for a LWR-based economy that is supported by some fraction of FSBs?

b) What is the impact on regional and world nuclear energy demand if the FSB route to dealing with LWR-generated plutonium is taken?

c) To what extent and on what time scale are accumulated plutonium inventories diminished by specific FSB approaches, and to what extent are plutonium inventories actually destroyed versus merely shifted (e.g., from accumulated LWR spent fuel to active FSB inventories, including integral processing)?

d) Do significant top-level differences exist for ATW versus LMR approaches to plutonium management via FSBs?

While generally efficient in terms of the fraction of total thermal power that is delivered for sale on the electrical grid, the LMR requires non-zero plutonium conversion ratios [21] for reasons of neutronic stability. This constraint results in a non-zero internal "circulation" of plutonium and a corresponding diminution of capacity to serve LWR clients.

The accelerator-based (ATW) approach to FSBs has no intrinsic, safety-driven need to "recirculate" plutonium, but the ATW has a higher recirculating power requirement and a higher capital cost; both of these requirements reflect burdens associated with the accelerator needed to drive a subcritical target/blanket system. High intrinsic plutonium inventories are associated with the LMR (and possibly ATW), however.

To begin addressing these questions, a simplified model [8] was implemented into the ERB model wherein the factor by which the cost of LWR-based nuclear energy would be increased was used to reflect the economic penalty associated with a particular FSB scheme back to the market-share determination. This factor is a function of the support ratio of FSBs to LWRs based on the fraction of the total nuclear capacity provided by the FSBs in a given global region at a given time. The support ratio is controlled by an exogenously specified prescription that gives the rate at which accumulated plutonium can/should be reduced. Additionally, the (maximum) magnitude and deployment rate of FSB capacity is constrained [8].

The FSB results presented here are limited to departures from the once-through LWR basis scenario. More comprehensive analysis of optimal ways to manage civilian plutonium must balance: a) the "real" (and presently undetermined) cost of direct disposal of LWR spent fuel; and b) the costs of LWR recycle as a front-end burner compared to more expensive FSB systems having as a main attribute the ability to deal with plutonium forms that cannot be efficiently burned in LWRs.

Only regional scenarios for FSB deployment have been considered. Supra-regional implementation and greater cost sharing may present a more economic approach that remains to be examined. Generally, the results of the constrained deployment algorithm [8] for any given region depend on the growth of nuclear power and plutonium inventories in that region and on the magnitude of the constraints imposed on FSB deployment rates and magnitudes (relative to LWR capacity). Regions with a longer history of nuclear power and accumulated plutonium begin at the constrained FSB capacity, and, depending on subsequent growths in nuclear energy, fall below that limit later in the 21st century. The reformed economy regions are intermediate in reaching that limit, and the developing regions do not come close to reaching the FSB capacity limit.

For the LWR *versus* LMR financial and costing parameters used (a minimum capital cost penalty of 50 percent for FSBs and somewhat higher fixed charge rates [higher risk] and operating and maintenance charges), the cost impact is significant (~30%) for "heavy users" during the early deployment of LMR-based FSBs (when the demand is high and the support ratio is at the constrained lower value). Later in time, when LWR-accumulated plutonium has diminished (*e.g.*, either burned or deployed in the high-inventory FSBs), the cost impact approaches the 10-15% level.

The nuclear energy costs passed back to determine market shares have been increased for each region at each time by the COE-increment factor described above. The impact of these increased costs on global nuclear energy demand is shown in Fig. 10, where three FSB scenarios are compared with the basis scenario, as well as the IAEA high/medium/low-demand scenarios [7]. The three FSB scenarios are: LMR with plutonium conversion ratios of 0.6 and 0.2, and ATW with a zero conversion ratio, reduced intrinsic plutonium inventory, reduced engineering gain, and increased unit total cost (~17 percent more than the LMR [8]). The impact of reducing the capital cost of LMRs relative to LWRs from 1.5 to 1.1 is also shown in Fig. 10. Within the uncertainty of this highly aggregated costing model, the LMR/FSB and the ATW/FSB appear to trade the economics of internally circulated plutonium for internally circulated power to give nominally the same (low) support ratio and elevated values of cost of electricity.

The temporal and regional impacts on LWR-accumulated plutonium inventories for the 0.6 conversion ratio LMR and the moderate recirculating power ATW scenarios are reported in Ref. [8]. For all cases, the constrained limit on FSB deployment rate was encountered for all regions at all times. The constrained implementation rate was found to be insufficient to hold down the growth of accumulated plutonium in the China region in later periods. While the decreases in LWR-accumulated plutonium are significant, a large part of this plutonium is used to start up the high-inventory FSBs. Fully recycled and separated plutonium forms do not appear for this once-through LWR case, since the FSBs being considered invoke integral processing. Lastly, it should be noted that the comparison between the basis scenario and the FSB scenario must accommodate differences in demand for nuclear energy brought about by the expense of the adopted FSB schemes.
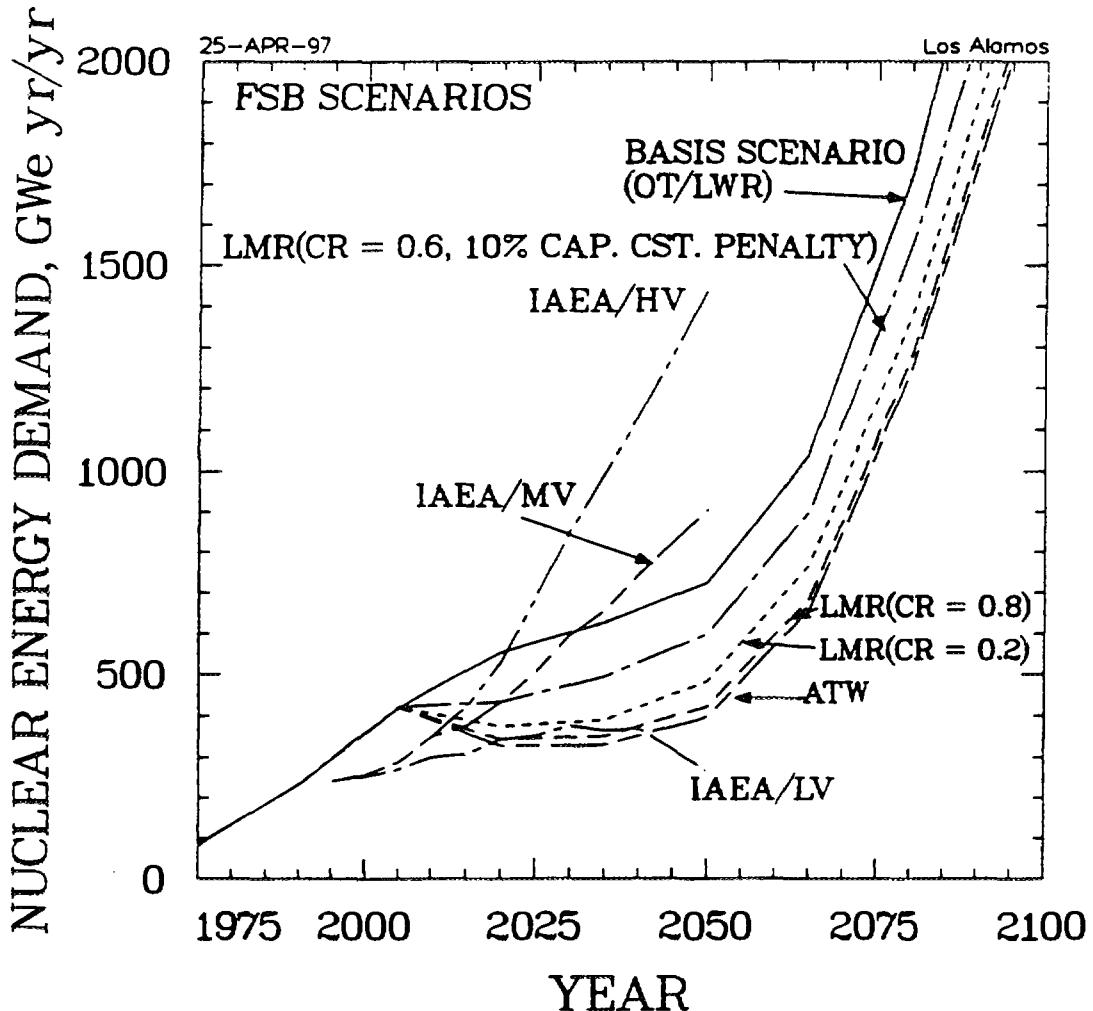
FIG. 10. *Impact of FSB implementation on nuclear energy demand for three scenarios [LMR(CR = 0.6); LMR(CR = 0.2), where CR is the conversion ratio; and ATW] as determined by the COE increases associated with more expensive FSBs operated synergistically with once-through LWRs; comparisons are made with the basis scenario and the Ref. [7] demand variants. The case with a lower cost penalty (FSB penalty reduced to within 10 percent of LWR costs) is shown for a LMR with CR = 0.6.*

4.   SUMMARY AND CONCLUSIONS

A range of long-term futures for nuclear energy has been examined by building relatively "surprise-free" scenarios using a consistent, but simplified, modeling tool. By varying a wide range of upper-level scenario attributes (external forces), a spectrum of remarkably similar nuclear energy demand scenarios can be generated. Although these scenarios represent only possibilities, they nevertheless provide a quantitative basis and connectivity for examining impacts of the lower-level attributes (internal drivers) that influence directly the economic and operational character of nuclear power. Furthermore, although these analyses are "surprise free," the impacts of unexpected future events could possibly be interpreted if translation of the latter into terms that reflect upper-level hierarchical variations can be made.

Synoptic interim conclusions derived from each level of this analysis include:

a)   Upper-Level Hierarchical Variations: Nearly identical high, medium, and low nuclear energy variants [7] can be generated from a wide range of external drivers. A general,

61

consistent trend indicates continuation of the present demographics of nuclear energy (operation mainly in OECD countries) followed by a transition to developing nations dominance (particularly China) for times beyond 2050. Strong carbon taxation both reduces GHG emissions and widens the economic niche of nuclear energy, while moderately decreasing overall primary energy demand and GNP. Lowered nuclear cost (and increased nuclear share) by itself does not produce similar GHG impacts, indicating a need to explore non-electric applications of nuclear energy in competition with other sources of sustainable energy.

b) Lower-Level Hierarchical Variations: Interim conclusions for the three lower-level scenarios examined include:

- Once-Through or MOX-Recycle in LWRs: With growth in nuclear energy, so grows plutonium inventories. Depending on regional and temporal details of this scenario and the local demand generated for given upper-level scenario attributes, the places where this plutonium resides (in reactor, processing, spent fuel, *etc.*) will shift over time and region. Trends for the next 50 years follow those for demand scenarios in that the majority of plutonium will reside in industrialized states with a shift towards developing nations occurring later in the 21st century.

- Economically Competitive Breeders: Based solely on economic considerations, breeder reactors appear in the marketplace only if: a) conservative uranium-resource assumptions are invoked; b) relatively low capital costs are possible; and/or; c) significant costs for fossil fuel arise beyond the resource-depletion algorithms used in the ERB model (*e.g.*, strong carbon taxes globally applied, Fig. 5).

- Fast-Spectrum Burners: For the parameters used, systems based either on LMRs or accelerators, even when limited in (minimum) support ratio and deployment rate, can have significant impacts on nuclear energy cost and the demand that results. If the LMR requires a minimum conversion ratio (~0.6), this approach to dealing with the LWR-accumulating plutonium results in unattractive support ratios that increase the cost of the LWR-FSB synergy and decrease demand. The ATW offers an advantage in support ratio, but operation with a moderately multiplying blanket increases the recirculating power relative to the LMR, again increasing cost and reducing demand for the synergy.

Closing the nuclear fuel cycle in the broadest and long-term context means stemming growing quantities of plutonium while stably isolating hazardous fission product waste for times required to achieve benignity. The separation of plutonium from fission products followed by inventory reduction through recycle and burning can, under optimal conditions, extend resources, reduce proliferation risk, and conserve repository capacity. Economic penalties, however, will be incurred, but the impact of these penalties on overall demand for nuclear energy must be assessed in terms of the variability of the external drivers that establish the base demand scenario(s). The interim results presented herein point to directions where this desirable goal may reside, but considerably more real technical progress is needed before this desirable situation becomes a reality.

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SOME ASPECTS OF NUCLEAR POWER DEVELOPMENT IN RUSSIA AND STUDIES ON ITS OPTIMAL LONG TERM STRUCTURE

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Abstract

The paper presents the authors' outlook for nuclear power development in Russia. The analysis is based on the documents published and other materials as well as on the experience of the authors who participated in working out the state fuel-power program Power Strategy of Russia. The crucial point of the Strategy is that moratorium on the nuclear power development in Russia is inadmissible and a part of electricity production in the country will be covered by NPPs with increased safety. The studies which have been carried out by the organizations of MINATOM and ROSENERGOATOM and by some authors have shown that a potential of the Russia nuclear power complex meets the requirements of the nuclear power development up to year 2010. From the standpoint of the authors of the paper the investment climate in the country is the most important and uncertain factor influencing the program realization. But nuclear power preserves competitive ability in any option of new electric capacities introduced in Russia. Application of the market-oriented IAEA's planning tools have confirmed the competitive ability of nuclear power in the central region of Russia. This study is to be continued for other Russian regions. The estimates of the long-term prospects of nuclear power development in Russia made by the authors are based on the assumptions of natural uranium resources conservation, plutonium stockpile minimization and reduction of the radiotoxical waste to the lowest possible level. These requirements may be answered in the plutonium balanced system of thermal and fast reactors with a very economical consumption of natural uranium and a very small quantity of radioactive waste (mainly consisting of fission products and losses in reprocessing operations).

1. STATUS OF THE NUCLEAR POWER IN RUSSIA AND PRIORITIES OF ITS DEVELOPMENT

Russia has nine operating NPPs (29 units) with a total installed capacity of ~ 21.2 GWe. The 29 nuclear units in operation include: 13 with WWER PWRs (six WWER-440 and seven WWER-1000); 11 RBMK LWGRs; four EGP units of Bilibino NPP with channel water-graphite reactors; one fast neutron reactor BN-600. The contribution of nuclear power to the total electricity production in Russia is about 12% (more than 40% in some regions of the European part of Russia). All Russian nuclear units including fast neutron reactor BN-600 operate using uranium fuel. Annual spent fuel discharge amounts are about 800 t which contains about 4 t of plutonium and 0.3 t of minor actinides.

The fundamental directions of the nuclear power development in the country are determined in the **Power Strategy of Russia** [1] approved by the Government of the Russian Federation. The crucial point of the document is that a moratorium on nuclear power development in Russia is inadmissible and a part of the future electricity consumption will be covered by NPPs. Russia's decreasing oil and coal production - and the inevitable depletion of reserves of these fuels means that nuclear is one of the main guarantees of power supply security. The North-Western, Central and Northern Caucasus regions of Russia are the most suitable sites for NPPs.

The Power Strategy of Russia emphasizes the two principal stages of the Russian nuclear strategy:

1. Backfitting of existing nuclear power capacities through the next 10 to 15 years, completing the NPPs now under construction, developing and realizing designs of new-generation NPPs with increased safety;

2. Creating, in the nearest perspective, the preconditions for a considerable future increase of nuclear's contribution to the country's fuel balance ; and creating the base for a large-scale development of nuclear power after 2010 to generate up to 30-35% of Russia's total electricity generation and up to 40-50 % in the country's European part.

Realization of all the above stages will enable to [2]:

- diversify power production in the country and to provide economy of fuel and power resources to ensure their necessary export;
- create real conditions for increase of electricity export among European countries;
- create the base for easing Russian and European air pollution, e.g., the ecological policy stipulated by the **Power Strategy of Russia** aims at reducing the technological impact of fuel and power on the environment;
- solve the problem of utilization of accumulated power - and weapons-grade plutonium, and to dispose safely of radwaste, while developing fast neutron reactors and a closed fuel cycle.

According to the principles declared and on the basis of a detailed analysis of many factors of the nuclear power production the scale of nuclear power development for the next 10-15 years is determined by the **Power Strategy of Russia.**

The necessary nuclear level in 2010 would be 125 billion kWh (22 GW installed capacity)-i.e. 11% of the country's total electricity output. The maximum level of electricity production at NPPs in 2010 would be 160 billion kWh (28 GW installed capacity), i.e. up to 13 % of Russian's electricity production.

In the current period of economic transition in Russia there are many uncertainties which essentially complicate long-term forecasting of the expansion of the nuclear capacity. Thus, estimates of the possible variants differ to a great extent. On the other hand, the principal difference between the **Power Strategy of Russia** and the Power Programs of the former USSR should be emphasized. The **Power Strategy of Russia** is based on the new geopolitical situation, transition towards market-oriented, environmentally sound economies and also from the new function of the federal, regional and local authorities fixed in the Russian Constitution. The main task of the Strategy is not to determine the exact parameters of the future Russian fuel and power complex but to create the environment and conditions which could facilitate its development in the necessary direction.

2. SOME RUSSIAN REALITIES AFFECTING THE NUCLEAR POWER DEVELOPMENT UP TO 2010.

To determine the level of development of nuclear power and its structure, many factors are to be analyzed. Some of the major factors are as follows:

- Electricity demand expectations;
- Existence of natural uranium resources and their limits;
- Science and industry development level;
- Availability of up-to date nuclear power plant designs with safety features;

66

- The country's ecological safety and people health protection, public acceptance of the nuclear power;
- Economic indices for competition with conventional power.

Electricity demand . When analyzing the electricity demand in Russia the experts note the following paradox. On the one hand, the total power demand in the country has decreased while, on the other hand, there are regions of the Russian Federation with great electricity shortage. Even under existing conditions of economic stagnation the local governments of these regions are ready to support the construction of power plants.

The future electricity demand assessments for Russia were made for different options of the country's economic development [1], including the most optimistic and pessimistic forecast. Despite the fact that the highest priority of the Power Strategy is power saving, all the scenarios under consideration have shown an increase in the electricity consumption towards the year 2010 from 25% up to 40% above the existing level. If we also take into account the capacities of the power branch to be decommissioned by 2010, we may expect a rather bulky market of electricity demand .

Fuel . While a major problem of traditional fossil-fueled power plants is fuel supply which requires large capital investments, the nuclear power program up to 2010 could be run on already available cheap uranium stored. Thus, nuclear power is the only branch in the fuel and power complex structure which does not require mining in the immediate future. Even if we take into account for Russia's export of uranium products, there will be enough left to fuel any version of nuclear power development up to the year 2010 [1, 2].

Nuclear science, technology and component - manufacture. It is rather natural that the Chernobyl accident, the former USSR disintegration and economic stagnation negatively affected the nuclear science and technology potential in Russia. This potential was mainly concentrated at the territory of Russia and objectively has appeared surplus for the new and much lower rates of nuclear power development. All these circumstances have resulted in the very difficult and painful processes of reduction and restructurization of the nuclear domain. Nevertheless, existing industrial and construction enterprises and infrastructure still have a great potential. For the version of a maximum nuclear power development from 1997 to 2010 , the " Izora Plant" will make on average 1.38 sets of equipment per year with an average power of 782 MW/year; " Atommach" will make 1.62 sets per year with an average power of 1187 MW/year; "Leningrad Metals Plant" will run at 75-100% of its manufacturing capacity [2].

Therefore, the existing nuclear scientific, technical and industrial basis of Russia renders the program of nuclear power development up to year 2010 quite realistic, as well as carrying out of the perspective R&D and work on new designs.

New designs with improved safety features. New designs considered as priority for the construction of leading NPPs are [2]: WWER-640 (NP-500 design) with a capacity of 1800 MWth at the Sosnovyi Bor (Leningrad region) site; WWER-1000 (NP-1000, NP-1100 project) with a capacity of 3000-3300 MWth at the Novovoronezh NPP. Decrease of reactor capacity and of core power density in these designs gives additional opportunities for considerable rise of safety, while providing competitiveness. The fast neutron nuclear power installations BN-800 (2100 MWth) to be constructed at the two Ural sites are not only designed to generate electricity and district heating but to burn up weapons-grade plutonium and actinides. To supply energy to industry in remote areas, several designs of nuclear power installations and low-power NPPs (2.5 to 150 MWth) are available.

Safety, people's health, environmental protection and public acceptance. Does the nuclear fuel cycle really have ecological advantages when compared with the fissile fuel cycle or not? This question is very important for the further development of nuclear power.

Under normal operation radioactive contamination of the environment beyond the NPP site boundaries is within the natural background level. Stable NPP operation is one of the environmental improvement factors. The analysis of atmospheric releases of Russia's electricity power has shown that while producing about 12% of the total electricity in the country NPPs and nuclear fuel cycle plants are emitting only about 3% of sulfur dioxide, 0.5% of carbon monoxide and 0.9% of nitrogen oxides. The public exposure near NPPs is determined by natural sources of radiation. The average annual dose of personnel at WWER and BN-type reactors is about ten times less than the maximum dose allowed.

But all these (and many other) ecological advantages of nuclear power can of course only be appreciated when the necessary safety level is ensured at the same time. Most Russian specialists and officials are aware that the nuclear industry is not prepared to face another accident approaching anywhere near the scale of Chernobyl. So there is a continuous effort to improve safety performance at all operating NPPs in Russia and most of the financial sources guaranteed for nuclear power of late (including return on capitalization) were invested in their reconstruction and technical improvements.

Transition to market relations in the country presumes that a certain economic status is given to nuclear power and it implies a new and much more important role of the public opinion in the realization of the nuclear power program. The cooperation with the public and local authorities in the regions of NPP sites are gradually beginning to take shape. This process of adjusting to new realities is being much complicated by the irreconcilable and inconstructive opposition to nuclear power. The ecological aspects of nuclear power development are the main targets for criticism. Lately, to the traditional objects of attacks which have been nuclear safety and radioactive waste disposition a new one has been added, i.e. the ecological aspects of ex-weapons plutonium utilization options.

In any case anti-nuclear opposition in itself is a new reality of nuclear power development in Russia and it should be taken into account in the same way as other factors for its development in the near future.

Economics. Most of the factors which have been considered above reflect the existing possibilities of the Russian nuclear sector and gives an opportunity to make an optimistic power projection up to 2015 . It is supposed that units at Rostov, Kalinin and Kursk NPPs will be put into operation in 1999-2000. At the same time, the first generation NPPs of about 9 GW installed capacity are being decommissioned before 2010. As regards the units of the second generation, MINATOM's policy set the task to consider the possibility for 5-10 years of operation life extension beyond the design operation life.

Unfortunately, the economic situation in the country requires at the same time a more careful outlook. The immense capital investment costs, long licensing and construction periods and return on capitalization are not in favor of nuclear power in the existing investment climate in the country. In the authors' opinion, the investment problems are among the weakest links in the Russian nuclear power program up to 2010 and it requires the consideration of a pessimistic option which is close to a simple compensation of removed capacity (Fig.1).

But, of course, an unfavorable investment climate may not only slow down nuclear power development. The financial obstacles mentioned above are typical for the fuel-power branch as a whole. Thus, key questions to be answered in the economic area are: has nuclear power sufficient competitive ability in realistic scenarios of power development in Russia and what regions are the most suitable sites?
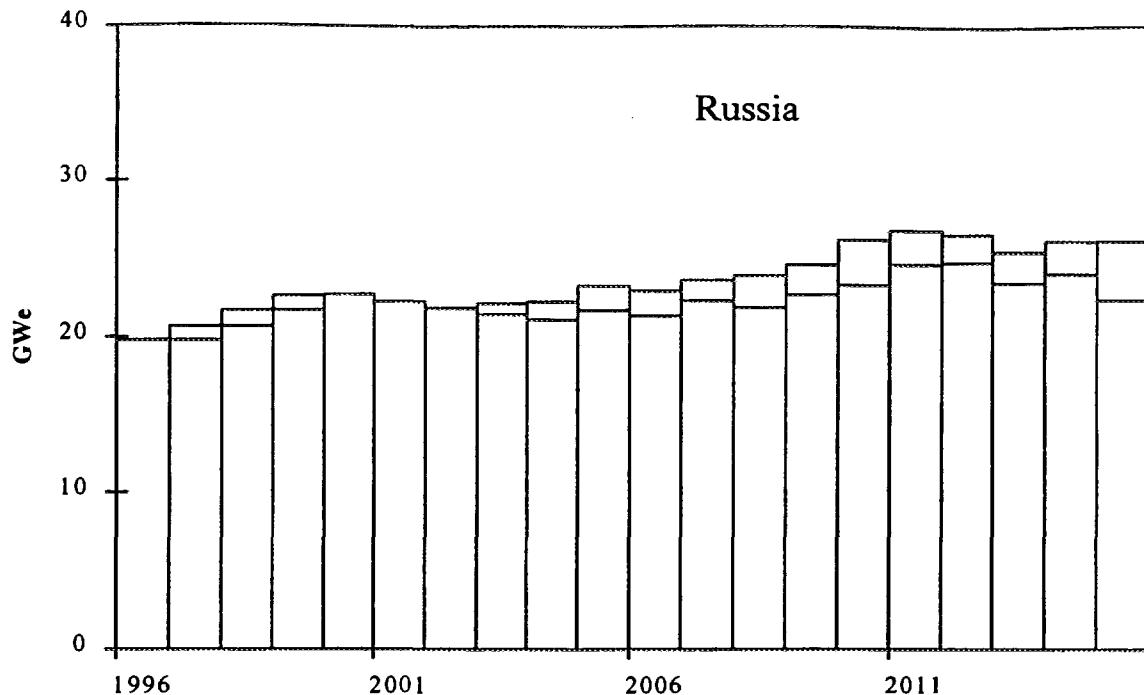
FIG. 1. Russia Nuclear Power Outlook to 2015.

3. ASSESSMENT OF NUCLEAR POWER COMPETITIVENESS IN SOME REGIONS OF RUSSIA WITH IAEA'S PLANNING TOOLS

Nowadays, economic methods and tools used in Russia are being adapted to the realities of market relations forming in the country.

In the process of analysing the competitive ability of NPPs on the Russian power market it is highly desirable to utilize a sound methodology allowing to properly account for the related technical, economic and environmental issues and thus to provide reliable information to decision-makers. In this respect, the use of energy planning tools supported and distributed by the IAEA that are widely used for energy planning purposes in many countries can become a valuable input to the process of the preparation of the strategy and, as a complement to other national studies, can provide important information for making decisions on further development of nuclear power in Russia.

Several IAEA planning tools were applied in Russia [3]. They included some modules of the ENPEP [4] package, the Wien Automatic Planning Package WASP [5] being one of them, and the DECADES database system. The MACRO and DEMAND modules of ENPEP were used for making up electricity demand projections in Russia; the WASP model was used for assessing the long-term role of nuclear power on the basis of development of an optimal capacity expansion plan for one of Russia's regions; finally the DECADES package was used for the development of a database of technical, economic and environmental parameters of various electricity generation chains and for a chain-by-chain comparison of the nuclear electricity generation chains with their competitors.

As the object of the WASP application [3], a power pool serving a large territory in the centre of Russia was selected. This power pool, which is called the Central Power Pool (CPP), is the largest component of the integrated power system of Russia. The installed capacity of the CPP is ~ 50 GW or about 1/4 of the total electricity generation capacity in Russia. There are more than 80 power plants in the system. They include plants using fossil fuels, nuclear power plants and hydraulic plants.

The scenario of fuel price escalation was taken from [6] and is based on the assumption that the escalation of fuel prices to the world market level is part of the consequences of the transition to the market economy. Lower rates for nuclear fuel were also assumed: gas/fuel oil - ~7.5% year; coal - ~7% year; nuclear fuels - ~4.3% year. This is one of the potential sources of the economic competitiveness of nuclear power in the future.

The structure of the optimal capacity expansion plan developed with WASP-III Plus is shown in Fig. 2. One can see the structure of the optimal solution and note the following characteristic features of the optimal capacity expansion plan:

• Until 2004 there is no need for new electricity generation capacities due to the drop in demand in the 90s.

• The optimal solution includes four types of electricity generation: combined-cycle units, conventional gas-fired units, nuclear units and gas-turbines.

• At the beginning of the planning period (1994), gas-fired technologies are economically the best due to rather low gas prices at that time. However, as gas and coal become more and more expensive reflecting accelerated escalation of fossil fuel prices, nuclear power becomes competitive and nuclear units start to enter the optimal solution. As a result, it is the nuclear unit that enters the system first when new capacities are required (2004). At the end of the considered period (2015) there are two nuclear units in the system. The remaining part of the new capacities are mostly gas-fired units with combined-cycle units being predominant.

• There are no inputs of new coal-fired units in the optimal solution, the reason being too high capital costs.

On the whole the results obtained by using IAEA's planning tools are very near to those obtained with the use of the new domestic methods and tools. The wide analysis of the competitive ability of designed NPPs on the Russian power market, if compared with fossile fuels, made it possible to determine the regions where the competitive ability of nuclear power is highest. Such regions have been determined together with the factors of admissible exceedings of the capital investments of NPPs over fossil fuel power plants.
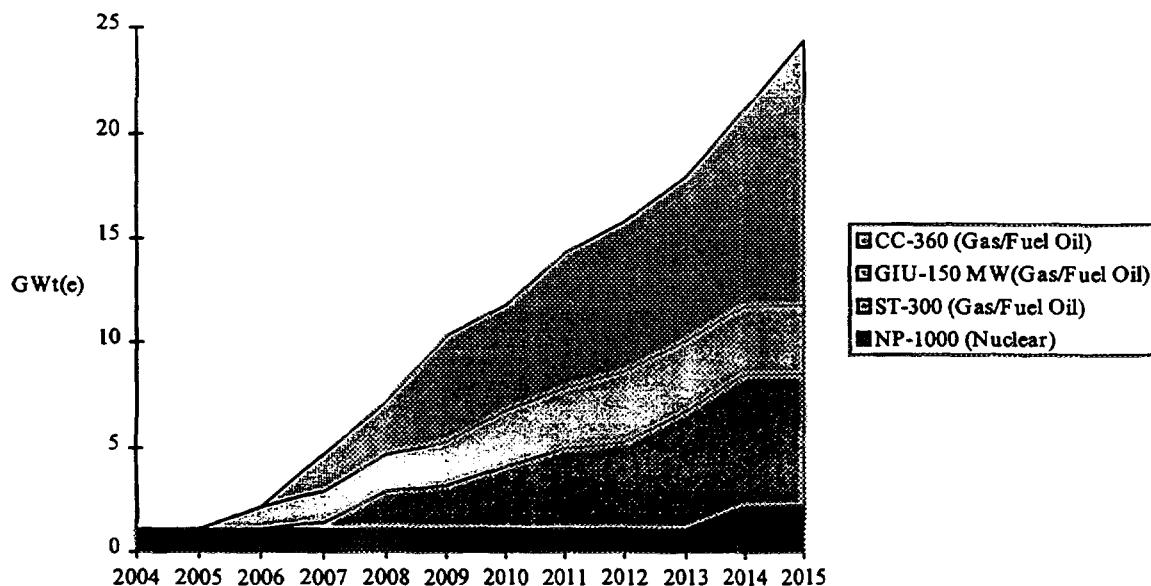
FIG. 2   Composition of the Variable System (Inputs of New Capacities).

70

It is worth mentioning that some authors of economic studies come to the conclusion that nuclear power is competitive almost all over Russia including Siberia [7].

4.   METHODOLOGICAL APPROACHES FOR EXTENDING THE HORIZON OF NUCLEAR PROJECTIONS BEYOND 2010

When speaking of the nuclear projections beyond 2010, economic assessments alone seem to be insufficient and ecological criteria much more reliable today. This is especially true if we take into account the still rather weak but very important tendencies in the world towards approaching economic and ecological criteria. We believe that, at the end of the road, ecologically safer systems would appear economically preferable.

The authors chose the following three issues among the many important ones that are related to this problem:

-    Conserving natural uranium resources and thereby decreasing the environmental impact at the initial stages of the nuclear fuel cycle;
-    Minimizing the plutonium stockpile;
-    Reducing radiotoxical waste to as low a level as modern methods can achieve (ALARA principle).

The country's nuclear power program up to 2010 could be run on already available cheap uranium stored but considering a more long-term perspective some experts point out that a new situation has arisen from the disintegration of the Soviet Union. Namely, total explored reserves of natural uranium are being estimated to amount to 450 thousand tons, reliably assured resources (RAR category of the IAEA classification) come to about 300 thousand tons [8] . Such reserves are not sufficient for 80 GWe nuclear power generation in thermal reactors after the year 2030, and for 50 GWe after the year 2040 (Fig. 3). Plutonium utilization is the most reliable way for Russia to provide itself with nuclear resources in the future. The alternative is buying uranium on the world market at world prices.

It is well known that the Russian strategy is based on the concept of fuel reprocessing and recycling reusable materials: uranium, plutonium and minor actinides. An available park of reactors and of new designs to be constructed in the nearest future make it possible to scrutinize the different structures of future reactor systems (Fig.4).

The open cycle in variants [1] and [2] is being realized now in Russia. The next variant ([3]) is the monorecycling cycle which is realized in Western Europe.

A specific feature of Russian nuclear power is the successful development of the fast reactor technology. It gives an opportunity to consider in a not too remote future the systems containing this type of reactors. Introducing fast reactors in the nuclear power structure with the aim to burn plutonium and minor actinides (neptunium, americium, curium) from the WWERs is the essence of variant [4]. The recovered uranium is recycled and reenriched and then returned to thermal reactors. Plutonium is recycled to provide at first the fissile material in WWERs and then to be used in BN-800 with the breeding ratio 0.8. All extracted minor actinides are utilized in fast reactors.

It is interesting to scrutinize also the two-stage system including WWER and BN reactors (variant [5]).

A monosystem of fast reactors with a breeding ratio equal to one is an asymptotic case of such a consideration (variant [6]).

thousand of tons

a - 50 GW installed capacity by 2030 and then stable level
b - 80 GW installed capacity by 2030 and then stable level

━━━━━━━━━━ thermal reactors

────────── fast reactors after 2030
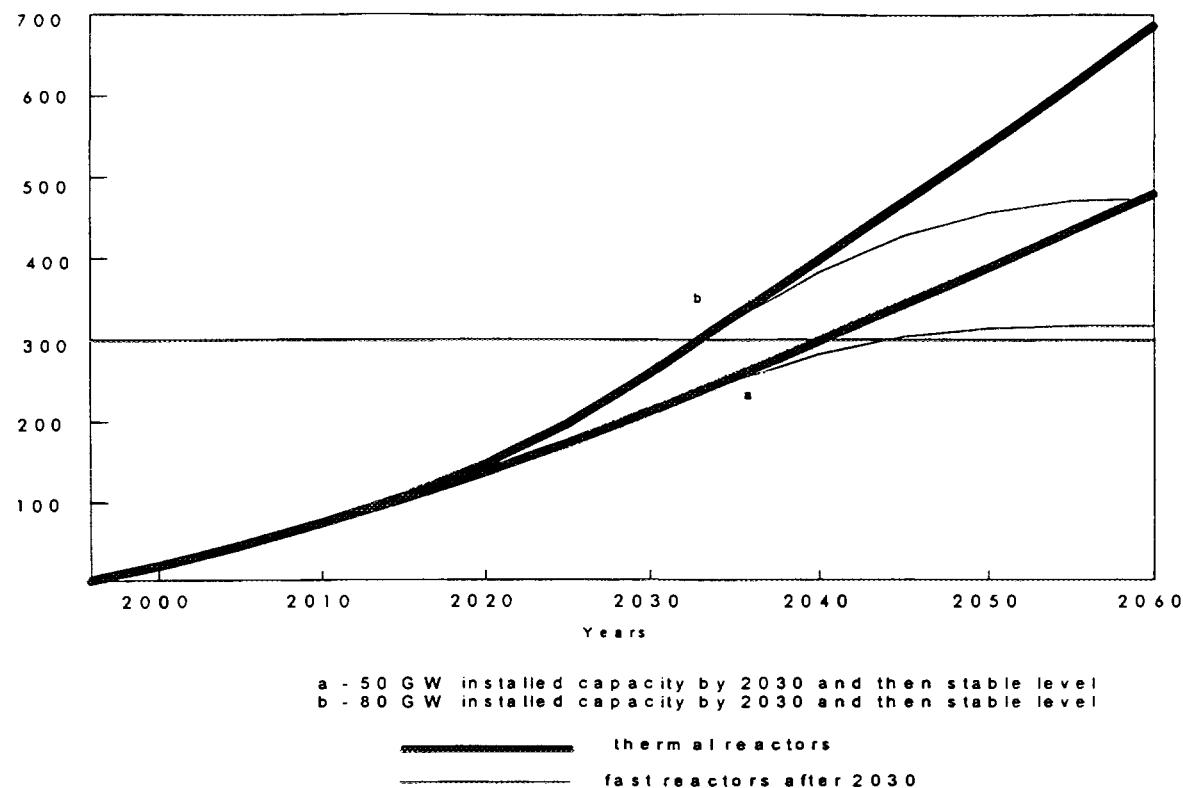
FIG. 3 Natural Uranium Demands for Russian Nuclear Power.

' scenarios   Open Cycle

1.   WWER (UOX) ──▶ Spent Fuel

2.   RBMK (UOX) ──▶ Spent Fuel

Monorecycling

3.   85% WWER (UOX) ──▶ 15% WWER (MOX) ──▶ Spent Fuel

Multiple Recycling in BN, BR=0.8

4.   59% WWER (UOX) ──▶ 10% WWER (MOX) ──▶ 31% BN(ÎÎÕ) ──▶ WASTES

5.   53% WWER (UOX) ──▶ 47% BN (ÎÎÕ) ──▶ WASTES

Multiple Recycling in BN, BR=1

6.   100% BN ──▶ WASTES
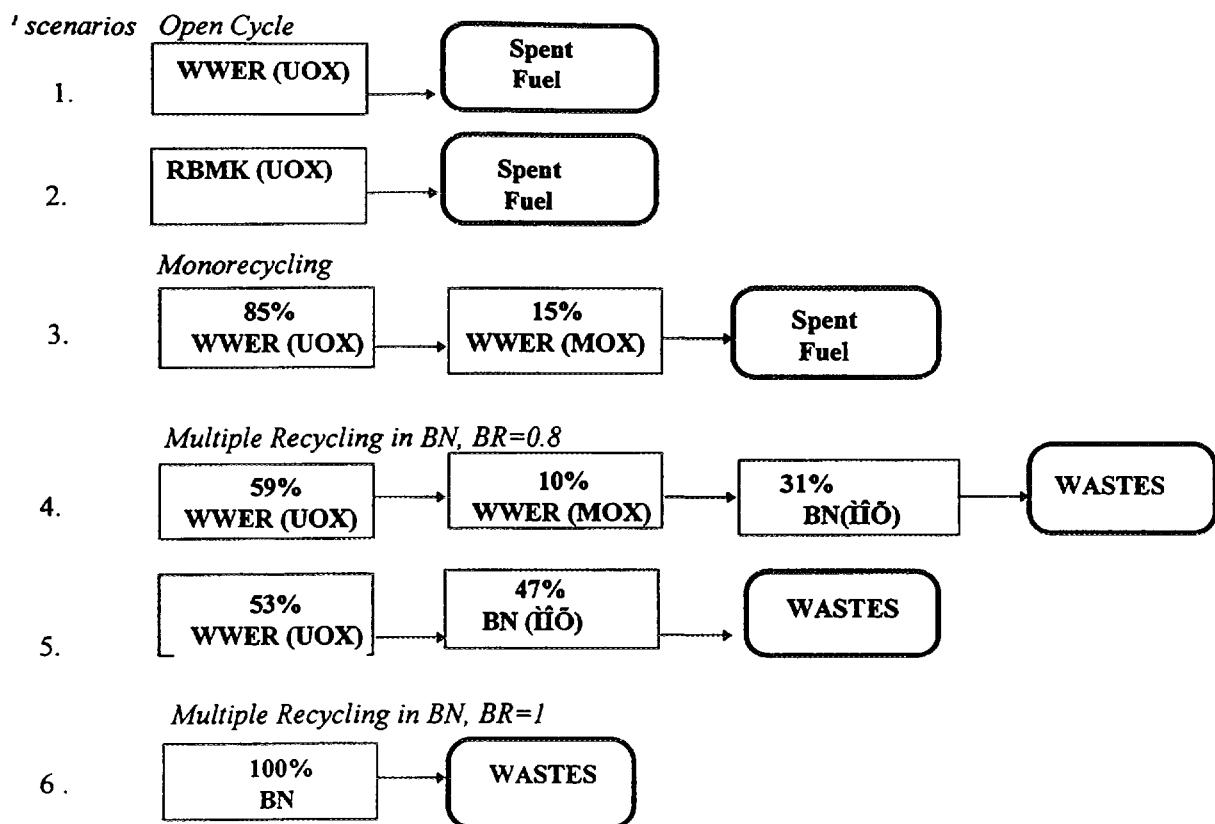
FIG. 4   Scenario of Nuclear Power Development Based on WWER-1000, BN-800 Reactors.

72

It is necessary to note that due to its splendid physical properties the fast reactor may ensure breeding of the nuclear fuel as well as burning of the excess fissile materials. Moreover, switching over from one function to another is possible at the reactor unit by changing only the core.

The results of our study are represented in Figures 5-8.

One can see that monorecycling (variant [1] 3) provides an opportunity to ensure nuclear power generation up to year 2030 with the use of reliably assured uranium resources alone and then to maintain during 30 years nuclear power generation with an installed capacity of about 20% more than in the strategy based on the open cycle (Fig. 5). The specific need for natural uranium resources is reduced by 1.4 times when compared with variants [1] 1 and [1] 2 (Fig. 6).

This option saves about 100 thousand tons of natural uranium for 50 GWe nuclear power generation operating 30-35 years, or approximately half of the country's uranium resources with the price remaining below $ 80 per kg. At the same time, as shown in Figure 5, once-through recycling in thermal reactors will only postpone the problem of uranium deficit but not resolve it even for a century.

One can mark the significant decrease of the specific radwaste mass in variant [1] 3: to a factor of 3 compared with open cycle option [1] 1 and to a factor of 6 compared with option [1] 2 (Fig. 7). But the reduction of the specific mass of plutonium and minor actinides is not so essential. Moreover, the specific mass of minor actinides in spent fuel in variant [1] 3 is even increased compared with variants [1] 1 and [1] 2 . In fact, PWRs are not good instruments for the transmutation of minor actinides, the capture cross section for them being much larger than the one for fission.

The introduction of BN-800 type reactors into the system - the installations with a hard spectrum of neutrons (variants [1] 5 and [1] 6) lead to a fundamentally new situation (Fig. 7- 8) . Uranium, plutonium and minor actinides will be "closed" in the cycle and their release into the environment will be insignificant and only inevitable losses from technological operations in chemical processing. Thus, nuclear wastes of the systems including fast reactors will consist mainly of fission products, which is 25-50 times less than the amount of radioactive wastes for the once-through fuel cycle.

Simultaneously, multirecycling allows for a further essential reduction of the need of resources to a factor of 2.5-4, when compared with the open cycle variants (Fig. 6). The "pure" system of fast reactors is the most effective from the point of view of uranium resource conservation, depleted uranium only is being consumed in the case. It is also very good from the standpoint of radwaste minimization, since the efficiency of heat conversion into electricity in fast reactors is more than in thermal ones. So, at the same level of electricity production, fast reactors need less amount of fuel to be fissioned.

In spite of the very good properties of the only fast reactors system the authors do not incline to consider any monosystem to be an asymptotically optimal structure.

Enriching of nuclear power with fast reactors seems to be rather a kind of beneficial tendency than a final aim. In the near future the wide introduction of fast reactors for nuclear power generation will be delayed by their high cost; in a more distant future, one may expect the creation of nuclear installations with qualitatively new properties in respect of nuclear safety and burning of long-lived fission products. System analysis of nuclear power development beyond 2010-2015 is a problem of exceptional difficulty and this study is, of course, only a tiny contribution to it. Nevertheless, the criteria of natural resources conservation, minimization of accumulated hazardous products and waste will be the reliable landmarks in any consideration since they make it possible to construct a nuclear power system in accordance with the natural ecosystems which are known to be an ideal model of interaction with the environment.
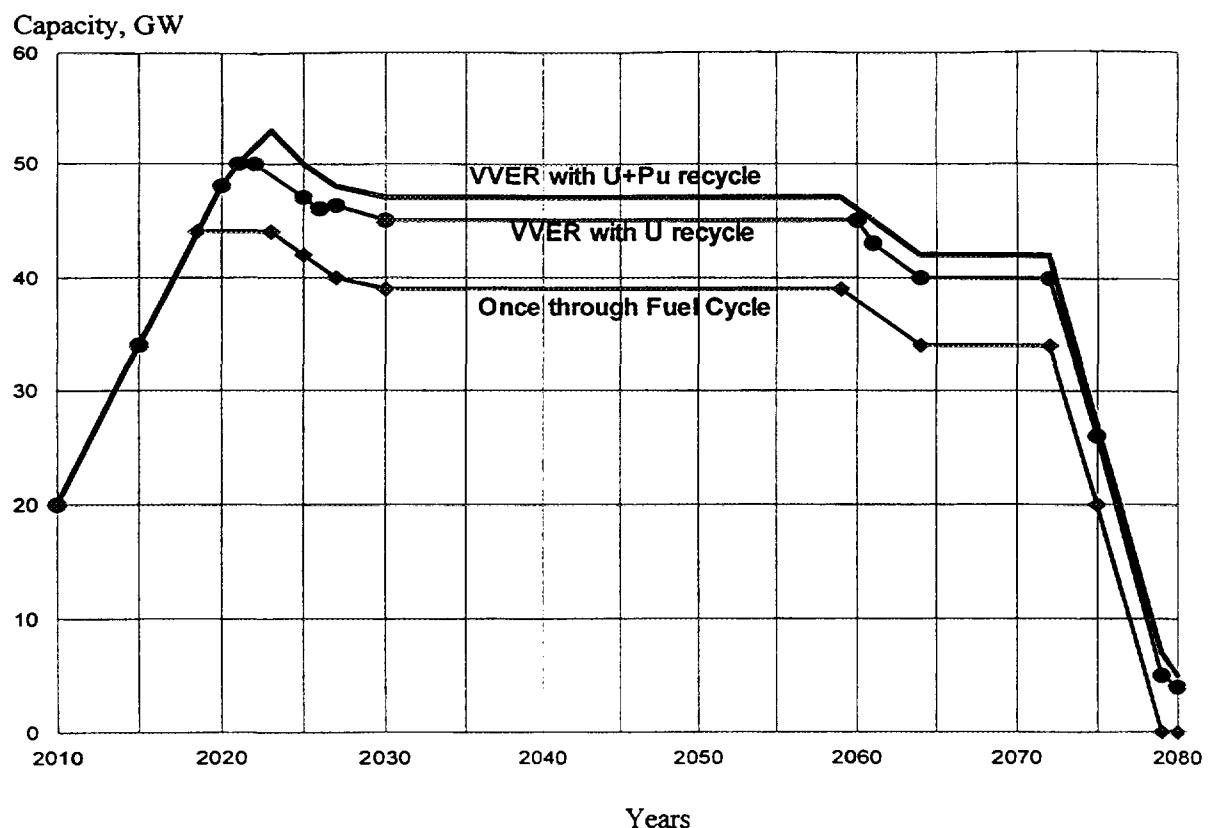
Capacity, GW

FIG. 5 The dynamics of NPP' capacity in once through and closed WWER nuclear fuel cycle

Natural Uranium Demands,
t/GWt(e)*
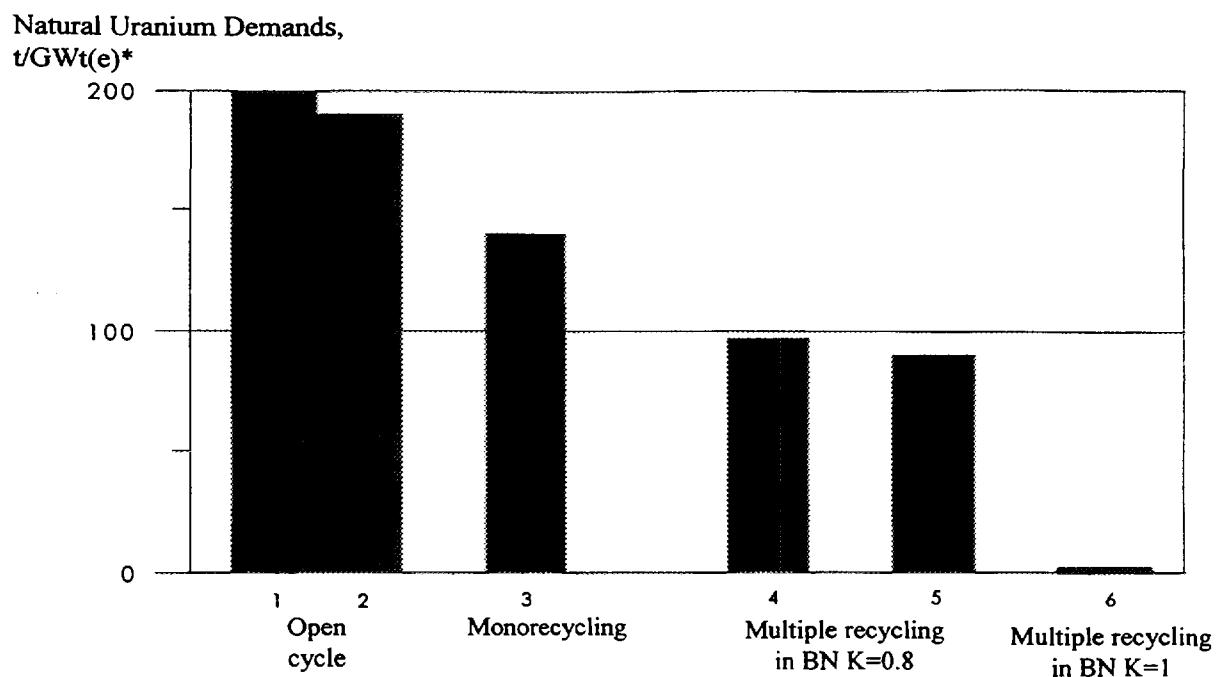
FIG .6   Specific Natural Uranium Demands for Different Scenarios of Nuclear Power
          Development

Spent Fuel and Radioactive Waste Mass,
    t/GWt(e)* year
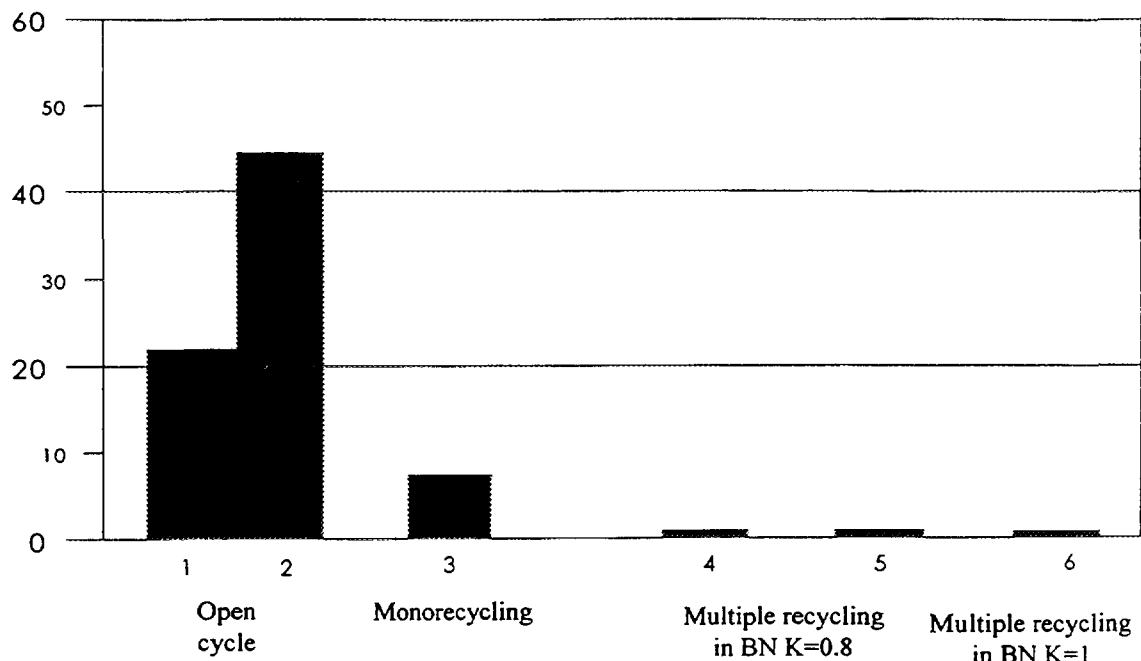
FIG. 7   Specific Spent Fuel and Radioactive Waste Masses for Different Scenario of
Nuclear Power Development.

Plutonium and Minor Actindes Mass,
t/GWt(e)*year
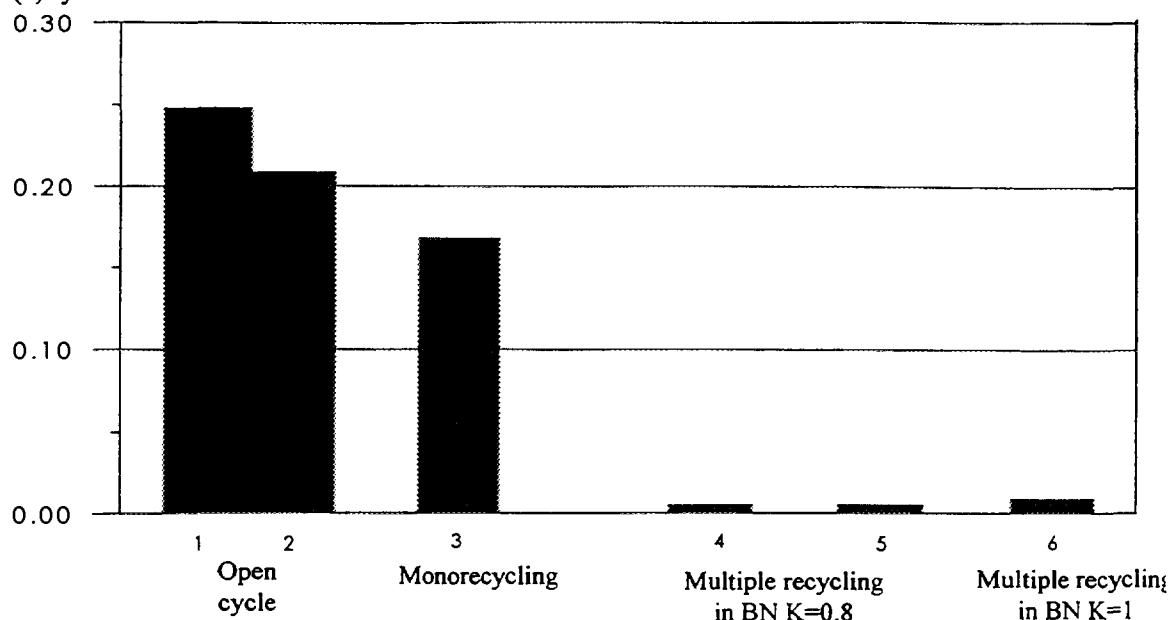
FIG. 8   Specific Plutonium and Minor Actinides Mass in Spent Fuel for Different Scenario of
Nuclear Power Development.

75

5. CONCLUSIONS

(1) In accordance with the Russian power strategy a moratorium on nuclear power development is inadmissible and a part of the electricity production in the country will be covered by nuclear power plants. Increasing of safety is the major priority of the nuclear policy.

(2) The market-oriented planning tools confirms the competitive ability of nuclear power in many regions of Russia, if compared with fossil fuels.

(3) From the authors standpoint the investment climate in the country is the most important and the most uncertain factor to influence the nuclear power development up to the year 2010.

(4) The plutonium balanced system of thermal and fast reactors has very good ecological properties from the standpoint of the conservation of natural uranium resources and of the waste minimization of uranium, plutonium and minor actinides.

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SESSION II

THE US PROGRAM FOR DISPOSITION OF
EXCESS WEAPONS PLUTONIUM

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Abstract

After an exhaustive interagency study, the United States has declared that 52.7 tons of plutonium, over half of its stockpile, is excess to its military needs, and has decided to pursue a dual-track approach to eliminating this excess stockpile, burning some of it once-through as power-reactor fuel, and immobilizing the remainder with intensely radioactive fission products. This effort represents a significant step toward increasing the irreversibility of nuclear arms reductions and reducing the risk of nuclear proliferation. The United States expects to complete disposition of this material over the next 2-3 decades, at a net discounted present cost of approximately $1.5 billion. International verification and stringent security and accounting for the material are planned for the entire program. Only a small number of U.S. reactors and relatively modest modifications to U.S. immobilization facilities will be required to implement the preferred approaches. Development and testing activities are already underway, and demonstrations of conversion of plutonium weapons components to oxide, immobilization of plutonium in large waste canisters, and use of fuel made from weapons plutonium in reactors are planned for the next several years. Large-scale implementation of plutonium disposition, however, is only likely to succeed if the United States and Russia reduce their excess plutonium stockpiles on parallel timescales. The dual-track approach, while controversial in the United States, is completely consistent with long-standing U.S. nonproliferation and fuel-cycle policies, which do not encourage reprocessing, and support reducing stockpiles of separated plutonium worldwide. In the author's view, the most important next step in plutonium disposition is establishing an international cooperative approach financing plutonium disposition in Russia. In addition, genuine irreversibility of nuclear arms reductions can only be achieved if current plans to retain large reserves allowing rapid increases in deployed nuclear arsenals are reversed, and an agreement reached to reduce *total* U.S. and Russian stockpiles of nuclear warheads and fissile materials to low levels. Success in these difficult endeavors will require a significant increase in high-level attention devoted to this critical international security problem.

1.   INTRODUCTION

Since the late 1980s, both the United States and Russia have been dismantling thousands of nuclear warheads, a process which continues to this day. This has left both countries with a daunting Cold War legacy: hundreds of tons of fissile materials that are no longer needed for military purposes, and must be safely and securely managed and ultimately used or disposed of.

The United States has declared that 52.7 tonnes of plutonium, over half of the 99.5 tons in the Department of Energy (DOE) and Department of Defense (DOD) stockpiles, is excess to its military needs, along with 175 tonnes of highly-enriched uranium (HEU) [1, 2]. President Clinton has committed that these stockpiles will never again be used in nuclear weapons, and DOE is undertaking a major storage and disposition effort, funded at over $100 million per year, designed to ensure that these materials are physically transformed in ways that will render them no more accessible and attractive for use in nuclear weapons than the plutonium in spent fuel from ordinary commercial nuclear reactors — a goal known as the "spent fuel standard." The United States sees this effort as a major step toward reducing the risks of nuclear proliferation and ensuring the irreversibility of nuclear arms reductions, and a clear signal of its commitment to these objectives.

In January, 1997, the United States confirmed its decision to pursue a dual-track approach to disposition of the excess weapons plutonium, using some of the material once-through as fuel in civilian reactors, and immobilizing the remainder as waste, mixed with intensely radioactive fission products [3]. The United States expects to implement this program over the next 2-3 decades, and hopes to work out arrangements so that Russia's excess fissile material stockpiles will be eliminated on a parallel timescale.

2. HISTORY OF THE U.S. PROGRAM

The U.S. plutonium disposition program formally began in September 1993, when President Clinton issued Presidential Decision Directive (PDD) 13, which laid out U.S. nonproliferation and export control policies. PDD-13 called for the United States to seek "to eliminate where possible the accumulation of stockpiles of highly-enriched uranium or plutonium, and to ensure that where these materials already exist they are subject to the highest standards of safety, security, and international accountability." In particular, the President's statement called for U.S. excess fissile materials to be placed under international safeguards, and called for "a comprehensive review of long-term options for plutonium disposition, taking into account technical, nonproliferation, environmental, budgetary and economic considerations." [4]

In response, an interagency group was established under the joint chairmanship of the Office of Science and Technology Policy and the National Security Council, to oversee plutonium disposition efforts and to ensure that the views of all relevant agencies were appropriately considered. In January, 1994, the Department of Energy, as the agency with primary responsibility within the United States government for the management and disposition of plutonium, established the Office of Fissile Materials Disposition to carry out this mission. The program received an important jump-start with the release of a report from the U.S. National Academy of Sciences, also in January 1994, which recommended a specific set of objectives for the U.S. disposition program and criteria by which the options should be judged, and identified the few options that best met those criteria and objectives: these recommendations provided a strong foundation from which to build, and were largely adopted by the U.S. government [5, 6].

The first step for the government's program, building from the Academy's work, was to identify the key options the U.S. program should focus on, out of the many dozens of ideas for dealing with excess plutonium which had been proposed. When the federal government is considering a major action having a significant effect on the environment — such as disposition of excess weapons plutonium — U.S. law requires an environmental impact statement comparing all of the "reasonable" alternatives. Thus, a central early focus of the U.S. program was a "screening" process which, by March of 1995, had ruled out a wide variety of alternatives as "unreasonable" — on grounds of undue cost, delay, technical uncertainty, environmental hazard, and the like. In particular, all options requiring development, testing, and deployment of new reactor types — including high-temperature gas reactors, new-design fast-neutron reactors, molten salt reactors, and accelerator-driven sub-critical systems, among others — were ruled out, not on ideological grounds, but because all of them would take longer, cost more, and involve more uncertainty than using reactors of existing types, which were adequate to the mission of transforming excess weapons plutonium to meet the spent fuel standard [7].

The screening process concluded that only three classes of alternatives were "reasonable" enough to require more detailed analysis and comparison: use of the excess plutonium as fuel in reactors of existing types; immobilization of plutonium with fission products; and direct disposal of plutonium in very deep boreholes. Each of these classes of alternatives included several options (e.g., light-water reactors (LWRs) and CANDUs, glass and ceramic, borehole disposal with and without prior immobilization), and a variety of variants of the particular options.

To decide which of these options to pursue, the program then began developing three types of information: environment, safety, and health information to support the required environmental impact statement; cost, schedule, and technical uncertainty data; and a detailed analysis of the arms reduction and nonproliferation impact of the different options [8-10]. This data was developed and refined during 1995-1996; for all three, there was an energetic effort to solicit and consider public comments.

In the United States, a wide variety of projects have been delayed for years as a result of lawsuits charging that their environmental documentation did not meet the requirements of the law. To avoid such an outcome, the U.S. disposition program focused a large fraction of its effort from the outset on the preparation of a comprehensive and defensible environmental impact statement. This focus led to concern from a variety of parties — including myself — that the program was moving too slowly, and was focused more on producing paper than on getting the job done. In the end, however, it seems clear that this focused effort was in fact the only way to get the project moving forward without being stymied from the outset by legal challenges — though such challenges will surely come in the future.

By mid-1996, the essential information needed to shape a decision was coming together. The U.S. national laboratories had developed an innovative process for converting plutonium weapons components or "pits" to oxide, which offered lower costs and dramatically lower waste generation in an integrated modular system. Both the existing reactor and immobilization alternatives looked viable. For the reactor alternative, detailed studies indicated that already-operating U.S. nuclear reactors could handle uranium-plutonium mixed-oxide (MOX) fuel in one-third of their reactors without major modifications, while remaining within existing safety envelopes, and that MOX in 100% of the reactor cores might well be possible. Canadian CANDU reactors also appeared to be capable of handling 100% MOX cores. Several U.S. utilities and the Ontario Hydro utility in Canada were actively interested in participating in the program (in anticipation of receiving either fees for irradiation services or, equivalently, heavily discounted fuel). It appeared that it might be possible to save money and time by modifying existing buildings in the DOE complex to serve as pit conversion and MOX fabrication facilities, rather than building new facilities from scratch.

For the immobilization alternative, a new concept, known as "can-in-canister," had been developed which would make it possible to make use of existing high-level waste immobilization operations without the need to substantially modify those facilities to handle plutonium. In this concept, the plutonium would be immobilized in a specially-designed glass or ceramic of its own, in relatively small cans. A number of these cans would be arrayed inside the huge canisters into which molten glass containing high-level waste is poured; the plutonium-bearing cans would then be embedded permanently within the intensely radioactive high-level waste canisters. (In the latest variant, the immobilized plutonium in the cans would be in the form of small pebbles, and the cans made of aluminum, which would melt when the HLW glass was poured over them, leaving the plutonium intimately mixed with the high-level waste glass.) With this concept, the immobilization of plutonium could be accomplished in small, critically-safe melters or ceramic production systems installed in existing glove-box lines. Moreover, by mid-1996, extensive work was indicating that both glass and ceramic forms could be designed to incorporate substantial quantities of plutonium, and a variety of potentially promising approaches to addressing the long-term repository criticality issue (which must be addressed for disposal of spent MOX fuel as well) were being developed. Like the reactor alternative, in short, it appeared clear that the immobilization alternative could be done safely and securely, in a reasonable time and for reasonable cost.

The deep borehole alternative, by contrast, was not looking as promising. From a purely technical perspective, the deep borehole alternative looked reasonably appealing, providing near-absolute protection against subnational diversion once the material was emplaced, considerable difficulty for retrieval by the host state (if designed for that purpose), and a strong argument for good environmental safety. But none of these benefits would accrue until the material was actually emplaced, and the cost, schedule, and feasibility for licensing a fundamentally new type of geologic repository were far too uncertain to make a major national security program dependent on success. The billions of dollars being spent on preparing the information needed for an eventual license application for the Yucca Mountain repository, and the continuing delays there, did not provide an encouraging analogy.

Ultimately, the DOE studies indicated that the costs, schedules, uncertainties, environmental implications, and nonproliferation and arms reduction implications of the reactor alternatives and the immobilization alternatives were roughly comparable; each approach had its own advantages and drawbacks, but none large enough to be decisive. Moreover, the studies indicated that pursuing *both* the reactor and immobilization alternatives — the so-called "hybrid" or "dual-track" alternative — would not be greatly more expensive, and would have substantial advantages. Pursuing both would provide higher confidence of success, and particularly higher confidence of an early start, since each alternative could serve as a backup in the event of unexpected difficulties and delays with the other. And pursuing both would involve the United States in the key technologies likely to be used in Russia's disposition program while simultaneously sending a clear signal of U.S. seriousness and flexibility in dealing with this critical international security problem, both of which would improve the potential for cooperation with Russia and other nations in getting the job done. Moreover, a dual-track approach would make it possible to use different approaches for different forms of plutonium: roughly a third of the U.S. excess plutonium inventory is in forms that would require expensive purification before they could be used as MOX fuel, and may therefore be more suitable for immobilization. Here, too, the U.S. National Academy of Sciences had led the way: in mid-1995, in the second volume of its study, the Academy had strongly recommended pursuing both of these approaches as quickly as practicable, "because it is crucial that at least one of these options succeed, because time is of the essence, and because the costs of pursuing both in parallel are modest in relation to the security stakes." [6, p. 14]

With these considerations in mind, after an extensive interagency discussion, in late 1996 the United States announced that its "preferred alternative" for disposition of its excess weapons plutonium was a dual-track approach including both use of plutonium in existing reactors and immobilization of plutonium. On January 14, 1997, that approach was confirmed in the formal "Record of Decision" required under U.S. law — a step personally approved by President Clinton [3]. The Department of Energy is now attempting to implement both tracks as rapidly as it can — and to cooperate with Russia to help ensure that when the time comes, Russia will be ready to eliminate its stocks of excess weapons plutonium in parallel.

3. REQUIREMENTS OF THE DUAL-TRACK APPROACH

To implement this dual-track approach will require additional detailed analyses and demonstrations, to provide the information necessary to select the best variants of both approaches and acquire needed licenses and approvals. It will also require a number of large-scale facilities, including a facility for converting pits to oxide (and preparing other forms of plutonium for disposition); a MOX fuel fabrication facility; reactors licensed to handle MOX fuel (neither U.S. nor Canadian reactors have such licenses currently); facilities for immobilizing plutonium; and facilities for immobilizing high-level wastes so as to combine the result with the immobilized plutonium. Neither the United States nor Russia has large-scale operational facilities for any of these purposes at the moment, and therefore several years and substantial initial capital investments will be required before large-scale disposition of excess weapons plutonium can begin.

Most aspects of the reactor approach can be considered technically demonstrated. Nearly two dozen LWRs around the world are already using MOX fuel, typically in one-third of their reactor cores [11]. It is very likely that the United States will ultimately choose to begin the reactor part of its disposition program using a one-third core approach based on this existing experience, and then shift to higher core loadings, possibly including 100% core, as the relevant issues are resolved and needed license modifications acquired. The United States has made clear that the pit conversion facility and MOX plant will be government-owned facilities on existing DOE sites, but that the government expects to contract with private firms to build and operate the fabrication plant and irradiate the fuel in existing utility reactors. DOE prefers to contract with a consortium representing both fabricators and reactor operators in a single package. The specific number of reactors to be used

has not yet been chosen, and depends on such factors as core loading and how much of the excess plutonium is to be used in reactors rather than being immobilized. To provide an order of magnitude, 50 tons of excess weapons plutonium could be irradiated to 42,000 megawatt-days per metric ton in 20 years in 9 1,000 megawatt-electric LWRs using one-third MOX cores, or 3 such reactors using full-MOX cores. Two CANDU reactors operating with full-core MOX could irradiate 50 tons of excess weapons plutonium over the same period; their fuel contains a lower percentage of plutonium, but would be irradiated to a much lower burnup, allowing them to accomplish the mission in somewhat fewer reactor-years of operation [12].

DOE expects that it will take a decade to bring a MOX plant into operation in the United States, and that the plant would remain operational for perhaps a dozen years before completing its mission in about 2018, after which it would be decommissioned [2]; a MOX plant capable of producing about 75 metric tons of heavy metal per year would be sufficient to accomplish the mission — or somewhat more for the CANDU alternative with its lower percentage of plutonium in MOX. The operation could begin several years earlier if existing European fabrication facilities — some of which are small and flexible enough to plausibly handle a specialty input material such as weapons plutonium — were used to fabricate initial test assemblies, and perhaps the first partial reactor cores. This approach was recommended by the U.S.-Russian Independent Scientific Commission on Disposition of Excess Plutonium, and has been favored by the U.S. nuclear industry, but DOE currently appears to be leaning against it [13].

Since the MOX option is largely technically demonstrated, the principal uncertainties facing its implementation in the United States are political and institutional. The controversy that has already arisen over the potential use of plutonium fuel in U.S. reactors suggests that it may ultimately prove to be very difficult to acquire the necessary political approvals and licenses to implement the MOX option in the United States, and substantial delays resulting from political and legal interventions remain a serious possibility.

With the immobilization approach, by contrast, while there are some political and institutional issues, the primary uncertainties are technical ones. While several countries around the world, including the United States and Russia, have demonstrated experience immobilizing high-level wastes, safely including large quantities of plutonium in this immobilization has never been done before.

To implement the "can-in-canister" immobilization approach, small, critically-safe melters or ceramic production machines could be installed in existing plutonium-handling glove-box lines, such as those that exist at the Savannah River Site, where current U.S. HLW immobilization operations are proceeding. To implement the dual track, a sufficient number of these melters would be installed to handle 2-3 tons of plutonium per year. The glass or ceramic prepared in these small facilities would contain between 5-12 percent plutonium by weight, and would also include substantial quantities of neutron absorbers, to ensure against criticality both in production and over thousands or millions of years in a geologic repository. Safeguards and security will have to be upgraded at the high-level waste immobilization facility, which is not currently designed for protection of plutonium-bearing materials. DOE estimates that immobilization using this approach could begin in about 7 years. For planning purposes, current DOE studies assume that only the one-third of the excess plutonium stockpile which is in impure forms would be immobilized; in that circumstance, the immobilization facility would only operate for about 6 years, while the MOX operation would continue for a long period thereafter [2, 8]. In my own view, it would make more sense to continue to operate both the MOX and immobilization facilities, allowing the completion of the overall mission to be accelerated by perhaps four years, and resulting in a roughly even split of the excess material between the MOX and immobilization options.

Remaining technical uncertainties facing the immobilization option include the performance of the various possible immobilization forms in a geologic repository (including the long-term

prospects for criticality); developing safe and effective approaches to the immobilization itself; choosing the type of neutron absorbers to be used, and the immobilization material best suited to incorporating both plutonium and neutron absorbers; and, perhaps most important from a policy perspective, developing and demonstrating safeguards approaches and technologies for this new type of plutonium processing. Contrary to the views expressed by some, it seems clear that the level of "irreversibility" offered by the immobilization approach would be similar, overall, to that offered by the reactor option: while the plutonium would remain weapon-grade, recovering 50 tons of plutonium from such forms would require hundreds of millions if not billions of dollars of expenditure over several years, and significant modifications to existing separation facilities would be needed.

As to cost, the two options are roughly comparable, at least as far as the uncertainties in current cost estimates permit a judgment. DOE estimates that the net discounted present cost of immobilizing 50 tons of plutonium, using the can-in-canister option, would be just over $1 billion. DOE estimates that burning 50 tons of excess plutonium as MOX fuel in the United States would have an excess net discounted present cost, compared to generating the same electricity with low-enriched uranium fuel, of just over $1.2 billion. The actual cost of fabricating the MOX fuel would be far higher than this, but DOE is including a "fuel credit" for the value of equivalent LEU fuel. In other words, the cost of preparing excess plutonium for fabrication and fabricating it into MOX fuel is so high that even fuel made from "free" plutonium is far more expensive than LEU fuel purchased on the open market. There is no money in excess plutonium — except, perhaps, on a nuclear black market. The additional cost of implementing both options at the same time is modest: DOE estimates a total discounted present cost for the hybrid approach of just under $1.5 billion [8]. These estimates do not yet include, however, the costs of "irradiation fees" likely to be demanded by U.S. utilities for the inconveniences of dealing with plutonium fuels, which will probably add a couple of hundred million to the total cost, somewhat increasing immobilization's estimated cost advantage.

4.   NEAR-TERM PLANS

DOE plans to move out rapidly with all of the technologies needed to implement the dual-track approach.

First, pit conversion and plutonium processing. This year, a complete pilot facility for pit conversion using the new U.S. process is being installed at the Los Alamos National Laboratory. This facility will be capable of processing 200 pits per year — or substantially more, if more than one shift were used. A full-scale facility capable of processing thousands of pits per year could be built by replicating this pilot line several times. This pilot-scale facility is scheduled to begin operations early next year. Development and testing are underway to ensure that the dry, hydride-based process to be used at this facility will produce a suitable oxide for MOX fuel fabrication, or to implement a fix if it does not. Development of a safeguards system that can accurately measure the unclassified, canned plutonium oxide product that results from the process, without revealing classified weapons information from earlier stages of the pit conversion process, is an integral part of the program.

Second, immobilization. DOE is working hard to settle the last remaining technical uncertainties with respect to immobilization, and plans to choose between glass and ceramic materials this September. (Based on the data available so far, my own view is that ceramic materials offer a superior alternative for this plutonium mission, though there is more current experience with waste immobilization in glass.) Full-size "cold tests" of the can-in-canister approach have been conducted at Savannah River, producing glass canisters using non-radioactive simulants for plutonium and high-level wastes, and laboratory-scale "hot tests" of the approach have also been completed. A full-size "hot test" at Savannah River may be possible as soon as the first half of next year. Unfortunately, at the moment very little work is being funded to develop new safeguards approaches for immobilization; in my view, this effort should be substantially expanded.

Third, reactors and MOX. DOE is now preparing a solicitation for consortia of firms to work together to build and operate the necessary MOX plant and irradiate the fuel in utility reactors. DOE hopes to choose the firms quickly, so that both fabricators and utilities can participate in fuel design and qualification from the earliest stages. Currently, initial "rodlets" of MOX pellets are being fabricated at Los Alamos, for irradiation in test reactors, in work designed to collect additional physics and fuel-performance data. This will eventually be followed by the fabrication and irradiation of lead assemblies for irradiation in utility reactors. As noted earlier, whether DOE will wait to fabricate these until a domestic facility becomes available or get an earlier start by having them fabricated in Europe remains uncertain.

Overall, then, DOE expects to carry out a broad program of tests and demonstrations of all the necessary technologies for disposition over the next several years. It is unlikely, however, that disposition of tens of tons of U.S. plutonium will occur before Russia is ready to reduce its excess plutonium stockpile in parallel.

5. PLUTONIUM DISPOSITION AND U S ARMS REDUCTION AND NONPROLIFERATION POLICY

President Clinton has publicly committed himself to the goal of irreversible nuclear arms reductions, and U.S. policy on excess fissile materials is intended as one part of an overall program to achieve that goal. The START agreements have so far limited only strategic launchers and delivery vehicles: once warheads are removed from their launchers, there is no requirement to dismantle them or even to account for what is done with them. This leaves the possibility that when reductions are carried out by simply reducing the number of warheads on missiles that remain in service — a process known as "downloading" — the reduction could in principle be rapidly reversed, by simply "uploading" the warheads back onto the missiles [12]. Because many of the U.S. reductions under START II (and START III, if it is successful) are to be achieved largely by such downloading, Russian officials have been particularly concerned about this potential for reversibility.

Fortunately, as a result of the Helsinki agreements [14], it appears that for the first time, the United States and Russia will grapple seriously with the issue of how to verify the dismantlement of the warheads themselves. Warheads that are disassembled, however, can also be reassembled, if the components remain available for military use: hence the critical importance of controlling and ultimately eliminating the excess stockpiles of fissile material resulting from dismantlement. As Minister of Atomic Energy Mikhailov has said, disarmament will genuinely be real when all of the extra weapons material has been converted for peaceful use.

The United States has taken several important first steps in this direction already [10]. First, the United States has declared that substantial fractions of its fissile material stockpiles are excess to its military needs, and has made a political commitment that these excess stockpiles of fissile material will never again be used in nuclear weapons — what might be called "political" irreversibility. Second, the United States has declared its intention to place these excess stockpiles under international safeguards to verify that they are not returned to weapons — "verified" irreversibility. Unfortunately, however, that process has been slow, and only about 12 tons of material is actually under safeguards today. The Moscow Nuclear Safety and Security Summit in April 1996 called for such steps to be taken with all excess fissile materials, and Russia has joined the United States and the IAEA in a trilateral process to work out specific arrangements for verifying the non-weapons use of excess materials [15]; nevertheless, to date, neither Russia nor any other weapon state has joined the United States in declaring former military material excess, committing not to use it in weapons, or placing it under IAEA safeguards.

Third, as described above, the United States is undertaking a major program to prepare to physically transform these excess materials in ways that would make it far more costly, time-

consuming, and observable to ever return them to weapons use — "physical" irreversibility. As noted earlier, this step will probably not be taken on a large scale unilaterally: if nothing else, it appears unlikely that Congress would provide the substantial funds required for disposition of U.S. excess plutonium if Russia were retaining its larger weapons plutonium stockpile in forms ready to put right back into nuclear weapons. Much the same can probably be said of Russia; hence, plutonium disposition is a job the two countries are going to do together, or not at all.

Plutonium disposition is also intended to serve the goals of non-proliferation — both by demonstrating the major nuclear weapon-states' commitment to their Article VI disarmament obligations, and by transforming large stockpiles of material into forms far less vulnerable to theft and diversion. As noted earlier, one of the fundamental goals of President Clinton's nonproliferation policy is to reduce stockpiles of separated, weapons-usable plutonium worldwide. Simply leaving this material in storage indefinitely would mean complete reliance on the continued effectiveness of whatever safeguarding arrangements are put in place to guard and monitor it; while the United States is confident in its own safeguarding arrangements, the ongoing economic crisis in the former Soviet states is creating new risks of theft and diversion that must be addressed. Fortunately, Russia, the United States, and other countries are quietly cooperating in a major program to install modern safeguards and security systems at the sites in the former Soviet Union where weapons-usable fissile materials are stored, and this program is making surprising progress. Nonetheless, the desirability of transforming as much material as possible into forms that pose less inherent proliferation risk is clear — as long as it can be done without a short-term increase in proliferation risk resulting from large-scale material processing and transport that is large enough to counteract the long-term benefit.

For these reasons, the assembled leaders at the Moscow nuclear summit unanimously concluded that disposition of excess fissile materials should be accomplished as quickly as possible, under international safeguards, and with stringent security and accounting measures ensuring effective nonproliferation controls.

Although plutonium disposition is intended to serve nonproliferation goals, some have seen the dual-track approach, with its acceptance of the use of excess weapons plutonium as fuel in nuclear reactors, as contradicting the long-standing U.S. nonproliferation policy of not supporting reprocessing and recycling of plutonium. Nothing could be further from the truth. As top officials from President Clinton on down have made clear, the United States is "not changing our fundamental policy toward nonproliferation and the nuclear fuel cycle." [16] The dual-track approach is about *eliminating* stockpiles of separated, weapons-usable plutonium that already exist, not about *producing* additional stockpiles of separated plutonium by reprocessing. Indeed, it is precisely because the United States feels so strongly about the proliferation risks posed by separated plutonium that it has decided to use both of the best technologies available — MOX in reactors and immobilization — to eliminate its excess stockpiles of this dangerous material as rapidly as possible. As such, the United States has committed that the spent fuel resulting from disposition will not be reprocessed, and that the government-owned MOX plant to be built for this mission will only be licensed for this mission and will be dismantled when it is complete.

Nevertheless, the dual-track decision has provoked fierce opposition from U.S. antinuclear groups, and from some in the nonproliferation community. It will continue to be controversial in the United States, and as DOE moves toward actually fabricating plutonium fuel and loading it into reactors, repeated political and legal attempts to block the effort can be expected.

Since this conference is on the future of the fuel cycle, let me say a few words about the U.S. policy against reprocessing and recycling of plutonium, and the reasons for it. First, despite the remarkable progress of safeguards technology, a world in which tens of tons of separated, weapons-usable plutonium is being produced, processed, and shipped from place to place every year — when a few kilograms is potentially enough for a bomb — clearly poses greater proliferation risks than a world in which that is not occurring. All separated plutonium, whether reactor-grade or weapon-

grade, poses serious proliferation risks. Since this latter point is often misunderstood, let me elaborate.

For an unsophisticated proliferator, making a crude bomb with a reliable, assured yield of a kiloton or more — and hence a destructive radius about one-third to one-half that of the Hiroshima bomb — from reactor-grade plutonium would require no more sophistication than making a bomb from weapon-grade plutonium. A somewhat more sophisticated proliferator could readily make bombs from reactor-grade plutonium with substantially higher reliable, assured yields. And major weapon states like the United States and Russia could, if they chose to do so, make bombs from reactor-grade plutonium with yield, weight, and reliability characteristics similar to those made from weapons-grade plutonium. That they have not chosen to do so in the past has to do with convenience and a desire to avoid radiation doses to workers and military personnel, not the difficulty of accomplishing the job. The United States has recently declassified an unprecedented level of detail on this subject, which I commend to your attention [10, pp. 37-39]. My colleagues from the National Academy of Sciences panel on plutonium disposition and I have spoken not only to designers from all three of the U.S. weapons laboratories on this subject, but also to weapons designers from all five of the declared weapon states; I think it is safe to assert that these points are not in dispute among weapon designers who have looked into the matter. Indeed, one Russian weapons-designer who has focused on this issue in detail criticized the information declassified by DOE for failing to point out that in some respects it would actually be *easier* for an unsophisticated proliferator to make a bomb from reactor-grade plutonium (as no neutron generator would be required). In short, the United States is concerned about the proliferation risks posed by large-scale handling of separated plutonium, and prefers not to encourage increases in these risks.

Second, with relatively low uranium prices, which are projected to continue for the foreseeable future, a once-through fuel cycle is clearly more cost-effective than a reprocessing fuel cycle. Hence, while a variety of U.S. utilities are interested in participating in a MOX disposition program, for which they expect to be paid, none of them are interested in reprocessing and recycling their own plutonium, for which they would have to pay more. Moreover, while the current abundance of cheap uranium has limited work on exploring how large the marginal supplies might be, a strong argument can be made that the uranium supply will last for at least fifty years, and more probably a century or more. And the increasingly diversified sources of supply worldwide should reduce concerns about fuel-supply security. In short: there is no real *need* for reprocessing and recycling now, or for decades to come [17].

Third, there do not appear to be major waste-management benefits from reprocessing. Performance assessments of potential geologic repositories routinely conclude that plutonium is a very minor contributor to the overall environmental risk from a nuclear waste repository; other isotopes, not separated by reprocessing, are even longer-lived, and far more mobile in a repository environment, making them a greater hazard to the biosphere. While reprocessing decreases the physical volume of high-level waste, the physical volume of the repository required is determined by the heat the rock can sustain, and the majority of the early heat is from the fission products, which are not separated by reprocessing. And reprocessing and recycle carries with it its own risks of accident and radiation release [18].

I do not expect everyone here to agree with these points of view. But the point is that the U.S. approach is *not* based on anti-nuclear ideology, but rather on a considered assessment of the pros and cons of the different approaches, which led to a conclusion that, for now and for the foreseeable future, reprocessing and recycle poses more risks than benefits.

6. THE WAY FORWARD: A PERSONAL VIEW

While the United States has undertaken a major fissile material disposition program, we are still a long way, today, from being in a position in which we can be confident that disposition of excess plutonium will in fact occur in the foreseeable future, or that the hoped-for improvement in the irreversibility of nuclear arms reductions will be achieved. A substantial increase in high-level political attention, the commitment of major financial resources from the international community, and significant changes in existing U.S. and Russian nuclear arms reduction policies will be necessary to get the job done.

The principle obstacle to implementing plutonium disposition in the United States is politics; the principle obstacle in Russia is money. The two are not unrelated. I believe that the political objections to implementing the dual-track in the United States — serious though they are — can be overcome if the program is part of a reciprocal disarmament package with Russia eliminating its excess stockpiles on a parallel track. But with an economic crisis so severe that even basic necessities such as wages and pensions are not being paid, Russia simply does not have the money to build the facilities needed to implement a plutonium disposition program. Given the very low cost of uranium fuel in Russia, it is highly unlikely that any substantial portion of the cost can be financed on a purely commercial basis through sales of the MOX fuel to Russian reactors. And the United States is unlikely to be willing to pay for 100% of the cost of its own plutonium disposition program, and 100% of the cost of Russia's program. This financial mystery — where will the money came from? — is, in my view, by far the largest obstacle that must be overcome if plutonium disposition is to be accomplished. Unfortunately, little progress toward resolving it has been made so far: despite the many discussions of this subject following the Moscow nuclear summit, including the Paris international experts' meeting in November of last year, there have as yet been no volunteers to pay any substantial fraction of the necessary cost.

Two general approaches to overcoming this obstacle can be envisioned. The international community could agree to share the cost through direct government contributions, as is being done to finance the shut-down of Chernobyl and the construction of new reactors in North Korea, to pick just two examples. The principal difficulty of such an approach is that governments would have to remain focused and committed for many years for it to succeed. Nevertheless, this is a serious possibility that ought to be further explored. The second general class of approach is some form of barter arrangement. For example, the French and German experts working with Russia on the proposed MOX pilot plant have considered an arrangement in which Cogema and Siemens would help MINATOM build a MOX plant in Russia, and would be paid with low-cost uranium and enrichment services, which they would sell on the international market. I have proposed a somewhat similar arrangement in which a joint venture would be established including MINATOM and Western fuel-cycle and construction firms: MINATOM would transfer 100 tons of excess HEU to this joint venture (above and beyond the 500 tons being sold to the United States), the Western governments would agree to open their restricted markets to this modest additional increment of material, and the joint venture would then be able to borrow the funds needed to build and operate the necessary facilities against the large asset represented by this 100 tons of HEU. This concept could potentially make it possible to finance plutonium disposition, create a management structure for implementing plutonium disposition that can sustain itself over the long term, eliminate an additional 100 tons of HEU, and provide substantial business to both MINATOM's desperate nuclear cities and to Western firms, all at little or no direct on-budget cost to the countries involved [19].

What matters is not so much which approach is chosen to solve this financing problem, but that the international community buckle down to the job of solving it — and soon. The Denver P-8 summit later this month is the place to begin; at a minimum, it is to be hoped that the summit will agree to task experts to begin preparing approaches for a later decision by the P-8 member states. While the Russian-French-German proposal for a MOX pilot plant in Russia is a useful idea that ought to be pursued, in the long run U.S. participation and support is likely to be essential to success.

A preliminary agreement between the United States and Russia on what needs to be done, and joint U.S.-Russian efforts to convince the other states to take part, would dramatically increase the chances for progress.

Is a near-term U.S.-Russian agreement of this kind possible? I believe so. While not making any specific financial commitment, the United States has expressed its willingness to support disposition of Russian plutonium, including the construction of a MOX plant in Russia, if four nonproliferation conditions are met: international safeguards throughout the disposition process (while protecting sensitive weapon design information); stringent security and accounting measures to prevent theft or diversion; use of a facility financed with help from the international community only for excess weapons plutonium, at least until disposition of that material is complete (since the international community would be contributing to the financing primarily for disarmament reasons); and no reprocessing of the spent fuel, at least until all of the excess weapons plutonium has been processed once through. None of these are particularly onerous, as they leave open what would be done with the relevant facilities once disposition is complete. They are an effort to do what has to be done: to bring countries that have common security interests in dealing with excess weapons plutonium together in a cooperative approach that does not compromise any of their diverging interests in the future of civilian plutonium.

In February of this year, John Holdren and Yevgeniy Velikhov, the co-chairmen of the U.S.-Russian Independent Scientific Commission on Disposition of Excess Weapons Plutonium — which was established by the U.S. and Russian governments to make recommendations to the two Presidents on how to proceed with plutonium disposition — wrote to Vice President Gore and Prime Minister Chernomyrdin, urging them to direct their governments to prepare an initial agreement which would: a) endorse implementation of the dual-track approach in both the United States and Russia; b) accept the U.S.-proposed non-proliferation conditions, to be implemented reciprocally in both countries; and c) commit both countries to work together with their P-8 partners to raise the necessary funds and establish an international entity that could implement such an international cooperative program. Agreement on these basic points remains as urgent and essential today as when that letter was written.

In addition to the financing issue, there is the issue of ensuring genuine irreversibility — and a comparable degree of irreversibility in the United States and Russia. If either country retains reserve stockpiles of warheads and fissile materials sufficient to rebuild a Cold War nuclear arsenal, plutonium disposition will not achieve its irreversibility purpose. Yet as far as can be determined from publicly available information, that is precisely the policy both countries are now pursuing. While the United States has declared more than half of its plutonium excess, the remainder is sufficient for a very large nuclear arsenal. It has now been officially declassified that the United States plans to retain a reserve of warheads and fissile materials sufficient to replace 100% of its deployed warheads — which is to say, sufficient to rapidly double its deployed arsenal [2]. If the fraction of its HEU that Russia has agreed to sell is any indication, Russia plans to do much the same. If genuine irreversibility is to be achieved, START III and associated agreements will have to address these "extra," reserve stockpiles, and reduce the *total* stockpiles of nuclear warheads and nuclear materials to the levels necessary to support the number of deployed warheads permitted by U.S.-Russian agreements — resulting in substantially larger quantities of excess material than have been declared to date. Verifying the total stockpiles of warheads and fissile materials will be a difficult task; the necessary regime of data declarations and inspections can and should be built step-by-step, with each new step adding to confidence while posing minimal risk in itself [5, 12].

This already tall order will be further complicated by the imbalance in total stockpiles. Russia's total stockpiles of warheads, plutonium, and HEU are all substantially larger than U.S. stockpiles — so to achieve parity at lower levels will require larger reductions on the Russian side. This principle of "reductions to equal levels, not equal reductions" has already been established in the START treaties. In the case of plutonium, unclassified U.S. estimates indicate that Russia has

approximately 200 tons of separated plutonium (including 30 tons of separated reactor-grade plutonium) compared to just under 100 tons for the United States [20]. If Russia simply declared 50 tons of this excess, to match the United States, it would have 150 tons remaining, while the United States would have less than 50, exacerbating the disparity rather than reducing it. Over time, the United States and Russia will have to negotiate an agreement specifying how much plutonium and HEU will be removed from their military stockpiles, and when; ideally, this agreement should call for reducing their remaining military stockpiles to low, equal levels. Work on the initial disposition demonstrations and facilities should not wait until such an agreement is completed, however.

In short, achieving the goals of plutonium disposition will require intensive efforts to arrange the necessary financing, and substantial revisions in the current nuclear arms policies of both the major states involved. Such measures will require a dramatic increase in the level of active and concerted attention to this issue from the highest levels of government. The job of disposition advocates, therefore, is to impress upon governments that eliminating the fissile legacies of the Cold War is an essential international security endeavor which must be accomplished as quickly as possible, and that what is required from Presidents and Ministers is not just endorsement in principle, but active engagement to get the job done.

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THE AIDA-MOX 1 PROGRAM: RESULTS OF THE FRENCH-RUSSIAN STUDY ON PEACEFUL USE OF PLUTONIUM FROM DISMANTLED RUSSIAN NUCLEAR WEAPONS

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Abstract

The Intergovernmental Agreement signed on November 12, 1992, between the governments of France and the Russian Federation instituted cooperation between the two countries for the safe elimination of the excess Russian nuclear weapons. France has allocated 400 million francs to this program, covering transportation and dismantling of nuclear weapons, interim storage and subsequent commercial use of the nuclear materials from the dismantled weapons, nuclear materials accountancy and safeguards, and scientific research.

The concept of loading commercial Russian reactors with fuel fabricated from the plutonium recovered from dismantled nuclear weapons of the former Soviet Union is gaining widespread acceptance, and is at the heart of the French-Russian AIDA/MOX project.

AIDA/MOX 1, one of the five topics of the AIDA program, is intended to specify a complete industrial system to reach this ambitious objective, i.e. to use plutonium recovered from Russian nuclear weapons to fabricate MOX fuel in Russia for currently operating or planned commercial Russian nuclear power plants to produce electricity while diminishing the weapons-grade plutonium inventory.

Broadly speaking, the PWR-MOX and FR-MOX options for using excess dismantled weapons plutonium for peaceful commercial nuclear power generating purposes — like the CANDU-MOX and HTR-MOX options offer several advantages over the remaining options (interim storage, disposal in vitrified form, etc.) notably from a nonproliferation standpoint.
The joint French-Russian studies carried out under the AÏDA/MOX 1 program have led to the following conclusions:

1) Using 30% MOX fuel is feasible in certain WWER 1000 reactors, after implementation of design changes similar to those made in France from 1985 to 1990 when EDF began using 30% MOX fuel in its 900 MW PWRs. These modifications (mainly affecting the number and design of the control rods, the soluble boron concentration in the water of some systems, and radiological protection of the fresh MOX fuel assembly

transfer system) are currently the subject of preliminary studies by the Russian and the French parties, and will be covered in detail in the subsequent phase (1997-1998) proposed under the AIDA/MOX 2 program. This option would enable dispose of about 270 kg of W-Pu annually per WWER-1000 reactor.

2)   Using 100% MOX fuel in the BN-600 fast reactor without breeding blankets is certainly the most promising option in a reasonable time frame (even though further studies are necessary to validate it) and should therefore be assigned medium-term priority. In the short term, the easily implemented BN-600 hybrid core solution should make it possible to use 240 kg of W-Pu per year. This solution complies with Russian safety requirements (negative void coefficient) by placing the MOX fuel around the periphery of the core (in the next-to-last ring) in limited quantities: less than 20% of the total number of fuel assemblies in the BN-600 core.

3)   Studies on converting W-Pu into MOX fuel have led to the definition of a *reference process* for a future facility or plant to be built in Russia.

The *reference process* chosen by the French and Russian specialists comprises:

-       acid dissolution of plutonium alloy in HNO_3 + HF
-       purification by extraction of plutonium nitrate
-       Pu oxalate precipitation and PuO_2 production
-       MOX fabrication using the COCA and MIMAS processes.
-       Additionally two process variants were considered, neither variant has been adopted to date for lack of sufficient industrial experience; further research and development work will be required in both cases.

1)   The capacity of a MOX facility to be built in Russia was determined by the possibility of consuming MOX fuel in Russian BN-600 and WWER-1000 reactors. The AÏDA/MOX Coordinating Committee initially selected the following Russian reactors:

-       BN-600 hybrid core option ($\Rightarrow$ 240 kg of W-Pu per year), as the first step toward the final objective of 100% MOX fuel in the BN-600 reactor core (1310 kg of W-Pu per year) and gradual removal of all the blankets,

-       four WWER-1000 reactors at the Balakovo NPP ($\Rightarrow$ 4 x 270 kg of W-Pu per year), hence a total capacity of around 1300 kg of W-Pu for the TOMOX-1300 facility, i.e. approximately 30 metric tons of MOX per year.

2)   Preliminary design work on the TOMOX-1300 facility implementing glove-box handling technology is underway in Russia with French participation by the CEA, COGEMA and SGN. The results will be available by mid-1997, together with a preliminary estimate of the total cost and itemized cost of the plant components; allowance will be made for the basic facilities already in place at Russian nuclear sites, including Chelyabinsk 65 and Krasnoyarsk 26.

3)   A detailed proposal for the TOMOX-1300 plant will be required in 1997-1998 before construction begins in the Russian Federation. The detailed proposal is planned for the AIDA/MOX 2 program stipulated in the proposed Trilateral Agreement between France, Germany and the Russian Federation. The TOMOX 1300 project will be implemented in two separate entities: TOMOX and DEMOX.

1.   INTRODUCTION

French aid in the safe dismantling of Russian nuclear weapons from 1992 to 1997 under the "AIDA" program was a natural outgrowth of the French Government's constant concern for active participation in both conventional and nuclear nonproliferation and disarmament. The AIDA program is the tangible application of the Intergovernmental Agreement signed on November 12, 1992, between the governments of France and the Russian Federation This agreement instituted cooperation between the two countries for the purpose of safely eliminating Russian nuclear weapons and using the resulting nuclear materials for commercial purposes. France has allocated 400 million francs to this program, covering transportation and dismantling of nuclear weapons, interim storage and subsequent commercial use of the nuclear materials from the dismantled weapons, nuclear materials accountancy and safeguards, and scientific research.

Within the scope of these agreements, the AIDA program covers the following points:

1) Supply of equipment:

- radiological protection and measuring equipment to ensure the safety and surveillance of weapons during transport, interim storage and dismantling;

- machine-tools (one vertical lathe and three cutting machines) for the nuclear warheads dismantling;

- overpacks to protect the Russian arms containers during transport from their current storage sites to the dismantling facilities.

2) Construction in Russia of a safe storage building for lithium and hydrogen-bearing materials from the thermonuclear weapons. The construction work should be completed by the end of 1997; the building will have sufficient capacity for over 3000 containers, and is designed to ensure the safety and security of the stored materials.

3) Performance of studies intended notably to demonstrate the feasibility of using weapons plutonium in commercial MOX fuel: these studies are known as the "AIDA/MOX 1" program.

The AIDA program is managed on the French side by an Interministerial Committee on Aid for Dismantling Nuclear Weapons, chaired by Admiral Francis Orsini, *charge de mission* in the Ministry of Defense; his Russian counterpart is the Minister of Nuclear Power, Mr. Victor Mikhailov. The CEA is the operator of the AIDA program, under the responsibility of M. de la Gravière. The co-chairmen of the Coordinating Committee are Xavier Ouin (Ministry of Industry) and Vice-Minister N.N. Yegorov (MINATOM).

Present Status of French-Russian Cooperation

Radiological protection and measuring equipment was delivered in January and September 1995 with subsequent training of the operating personnel. Machine tools were delivered in March 1996, with personnel training ensured by the CEA. The first high-integrity container overpacks were delivered in September 1996, and deliveries will continue throughout 1997. The deep foundations for the safe storage building were completed in 1996; turnkey delivery is scheduled for the second half of 1997.

The Final Report of the bilateral French-Russian survey of possible uses of weapons plutonium for commercial electric power generation (AIDA/MOX I program) will be internationally distributed in the first half of 1997. The Report provides the following recommendations:

- For the short term: the use of Russian weapons plutonium as MOX fuel in existing Russian BN 600 reactor and WWER 1000 units with the construction of a facility known as TOMOX 1300 in Russia for converting the plutonium into MOX fuel. The proposed MOX-fabrication capacity of 1300 kg of plutonium per year would be sufficient to supply the BN 600 reactor (about 1 metric ton of MOX fuel per year) and four WWER 1000 reactors (about 29 tons of MOX per year).

- For the medium and long-term: various scenarios involving the construction of new reactors (e.g. BN 800, WWER 640) loaded with 100% MOX fuel, designed to enhance the utilization rate of plutonium from dismantled Russian nuclear weapons for commercial electric power generating purposes.

2. FROM RUSSIAN WEAPONS TO MOX FUEL FOR RUSSIAN REACTORS

The concept of loading commercial Russian reactors with fuel fabricated from the plutonium recovered from dismantled nuclear weapons of the former Soviet Union is gaining widespread acceptance, and is at the heart of the French-Russian AIDA/MOX project.

A program of this scope implies the commitment of substantial technical and financial resources. Dismantling thousands of weapons and removing the fissionable materials that may be recycled (military grade plutonium and highly enriched uranium) and separating the thermonuclear materials (hydrogen isotopes) for storage are delicate and costly operations. French scientists and industrial firms have acquired considerable experience in the area of defense-related nuclear activities, in reprocessing spent commercial fuel and in the use of nuclear materials that may be recycled -- notably in the form of mixed uranium-plutonium oxide (MOX) fuel.

AIDA/MOX 1, one of the five topics of the AIDA program, is intended to specify a complete industrial system to reach this ambitious objective, i.e. to use plutonium recovered from Russian nuclear weapons to fabricate MOX fuel in Russia for currently operating or planned commercial Russian nuclear power plants to produce electricity while diminishing the weapons-grade plutonium inventory.

The CEA is the operator of the French-Russian Intergovernmental Agreement, and thus coordinates the French contributions to the AIDA/MOX 1 program by COGEMA, FRAMATOME and EDF. The Russian Ministry of Nuclear Power, MINATOM, has the same role with respect to the research organizations (RIAR, VNIINM, IPPE, Radium Institute, Kurchatov Institute) and project institutes (GSPI, GYDROPRESS, VNIPIET, etc.).

The initial results of these studies were presented jointly by the French and Russian parties at the GLOBAL '95 conference organized by the American Nuclear Society at Versailles in September 1995 [1,2,3,4]. The results obtained in 1996 were also jointly presented to the international scientific community during the "G7 + 1" Experts Meeting in Paris in October 1996 [5] and the American Nuclear Society's Winter Meeting in Washington DC in November 1996 [6,7,8,9]--in particular, the results of research on converting plutonium alloy from some warheads into nitrate and then into plutonium oxide for incorporation in MOX ceramic fuel: this technical exploit has not been achieved to date at industrial scale.

French work at Marcoule in the ATALANTE complex, at Cadarache in the Advanced Fuel Fabrication Research Laboratory (LEFCA) and at Bruyeres-le-Chatel led CEA scientists and their Russian partners to select four processes. Two of these are based on plutonium dissolution in hydrochloric or nitric acid, the third on direct oxidation and the fourth on pyrometallurgy. A reference process will eventually be selected for conversion of plutonium alloy, and for converting the plutonium nitrate to a mixture of uranium and plutonium oxides on the basis of current scientific results and on the industrial experience acquired.

The preliminary design work for a pilot facility known as TOMOX 1300 (Transformation of military Objects into MOX fuel) was contracted by the CEA to COGEMA and SGN in 1995. This project study implemented the direct oxidation process to produce plutonium oxide, followed by conventional mechanical milling of mixed oxide powder; it would allow the fabrication of about 30 metric tons of MOX fuel pellets annually, incorporated in fuel assemblies for Russian PWRs and FRs.

The TOMOX 1300 project study continued in 1996-1997 under CEA contracts with the Russian project institutes using the process in which plutonium alloy is dissolved by HNO_3 + HF, purified by extraction of plutonium nitrate, with subsequent oxalate precipitation and fabrication of

PuO$_2$. This study will yield a preliminary cost estimate for installing the process facilities on existing Russian nuclear sites.

Irrespective of the process and facility ultimately selected, the design is contingent on the total quantity of weapons-grade plutonium to be recycled, currently estimated at about 50 metric tons for the Russian Federation (the same quantity as announced by the United States in Paris at the G7+1 Experts Conference in October 1996). Will it be preferable to refurbish Russian facilities (e.g. the Complex 300 MOX fabrication plant at Chelyabinsk 65 or the RT2 plant at Krasnoyarsk 26), or to build one or more entirely new units? The AIDA/MOX 1 program calls for drafting a feasibility report on both options in 1997.

How much weapons-grade plutonium can be used as fuel by Russian power reactors each year? From a technical standpoint, the initial results of the studies conducted by the CEA, FRAMATOME, EDF and the Russian IPPE Institute at Obninsk suggest that a few hundred kilograms of plutonium could be used each year in MOX fuel, comprising 30% of the core load in a single WWER 1000 pressurized water reactor (seven WWER 1000s are now operating in Russia); this estimate remains to be demonstrated, together with an assessment of the required engineering modifications and their cost. The BN 600 fast reactor now operating at Byeloyarsk NPP with enriched UO$_2$ fuel could also use a few hundred kilograms of plutonium per year, assuming a limit of about 20% MOX in the core; the feasibility of this operation should be fully demonstrated by the end of 1998. If the BN 800 reactor is built, it could use up to 1700 kg of plutonium annually with a 100% MOX core. Four BN 800 reactors could consume fifty tons of Russian weapons plutonium in less than ten years. The future WWER 640 with a 100% MOX core should also contribute to meeting this objective. More realistically, and in the short term, operating the BN 600 at Byeloyarsk and the four WWER 1000s at Balakovo would allow the use of 1300 kg of weapons plutonium each year--i.e. the design capacity of the future TOMOX 1300 facility.

For the short and medium term, a broader international effort and financing are to be envisaged. Over the much longer term, the construction of facilities in Russia capable of using at least 5000 kg of weapons plutonium per year could be considered. Naturally, a project of this scope will depend on the conclusions of the international studies and especially on future Russian decisions concerning the construction of the first BN 800 fast reactor and additional WWER 1000 and WWER 640 light water reactors.

3.   MAIN CONCLUSIONS OF THE AIDA/MOX 1 PROGRAM

The French-Russian studies conducted from 1993 to 1996 under the AIDA/MOX 1 program established the advantages and technical feasibility of the W-Pu MOX option in certain existing nuclear reactors within the Russian Federation.

Broadly speaking, the PWR-MOX and FR-MOX options for using excess dismantled weapons plutonium for peaceful commercial nuclear power generating purposes--like the CANDU-MOX and HTR-MOX options--offer several advantages over the remaining options (interim storage, disposal in vitrified form, etc.) notably from a non-proliferation standpoint:

1)   high radioactivity of the final product, a spent MOX fuel assembly, making any addition of radioactivity unnecessary;

2)   fission of a significant fraction of the initial weapons plutonium: in the PWR-MOX scenario, some 30% of the W-Pu is converted into fission products after irradiation on the order of 40 GWd t-^{1};

3)   plutonium accountancy: the W-Pu is processed in an industrial cycle in facilities under permanent surveillance by the international organizations responsible for non-proliferation safeguards (IAEA),

4)   isotopic denaturing of the residual plutonium (around 70%): the 239Pu fraction diminishes and that of the even numbered isotopes (^{238}Pu, ^{240}Pu and ^{242}Pu) increases.

5)   conservation of natural resources: 50 metric tons of weapons-grade plutonium are capable of producing some 350 TWh of electric power;

6)   no additional nuclear waste (e.g. vitrified plutonium): the spent MOX fuel assembly replaces a spent UOX fuel assembly.

        Compared with the other MOX options, the PWR-MOX and FR-MOX options also offer the following major advantages:

1)   the LWR-MOX and FR-MOX options are the only ones implementing proven technology: over 400 metric tons of PWR and BWR-MOX fuel have already been fabricated in Europe, and 19 European reactors have been using MOX for a number of years; over 100 metric tons of FR-MOX fuel have been fabricated to date in Europe;

2)   the PWR-MOX and FR-MOX options are the only ones compatible with existing Russian reactors capable of using large quantities of W-Pu and known to be economically viable.

        Concerning the implementation of this option by the Russian Federation, the joint French-Russian studies carried out under the AIDA/MOX 1 program have led to the following conclusions:

1)   Using 30% MOX fuel is feasible in certain WWER 1000 reactors, after implementation of design changes similar to those made in France from 1985 to 1990 when EDF began using 30% MOX fuel in its 900 MW PWRs. These modifications (mainly affecting the number and design of the control rods, the soluble boron concentration in the water of some systems, and radiological protection of the fresh MOX fuel assembly transfer system) are currently the subject of preliminary studies by the Russian and the French parties, and will be covered in detail in the subsequent phase (1997-1998) proposed under the AIDA/MOX 2 program. This option would enable dispositioning of about 270 kg of W-Pu annually per WWER 1000 reactor (Figure 1).

2)   Using 100% MOX fuel in the BN 600 fast reactor without breeding blankets is certainly the most promising option in a reasonable time frame (even though further studies are necessary to validate it) and should therefore be assigned medium-term priority. In the short term, the easily implemented BN 600 hybrid core solution should make it possible to use 240 kg of W-Pu per year. This solution complies with Russian safety requirements (negative void coefficient) by placing the MOX fuel around the periphery of the core (in the next-to-last ring) in limited quantities: less than 20% of the total number of fuel assemblies in the BN 600 core (Figure 2).

3)   Studies on converting W-Pu into MOX fuel have led to the definition of a *reference process* and two possible variants for a future facility or plant to be built in Russia.

98

The *reference process* chosen by the French and Russian specialists (Figure 3) comprises:

- acid dissolution of plutonium alloy in HNO₃ + HF
- purification by extraction of plutonium nitrate
- Pu oxalate precipitation and PuO₂ production
- MOX fabrication using the COCA and MIMAS processes.

The first process variant is the following:

- acid dissolution of plutonium alloy in HNO₃ + HF
- purification by extraction of plutonium nitrate
- coprecipitation of (U,Pu)O₂ with ammonia
- MOX fabrication by powder blending.
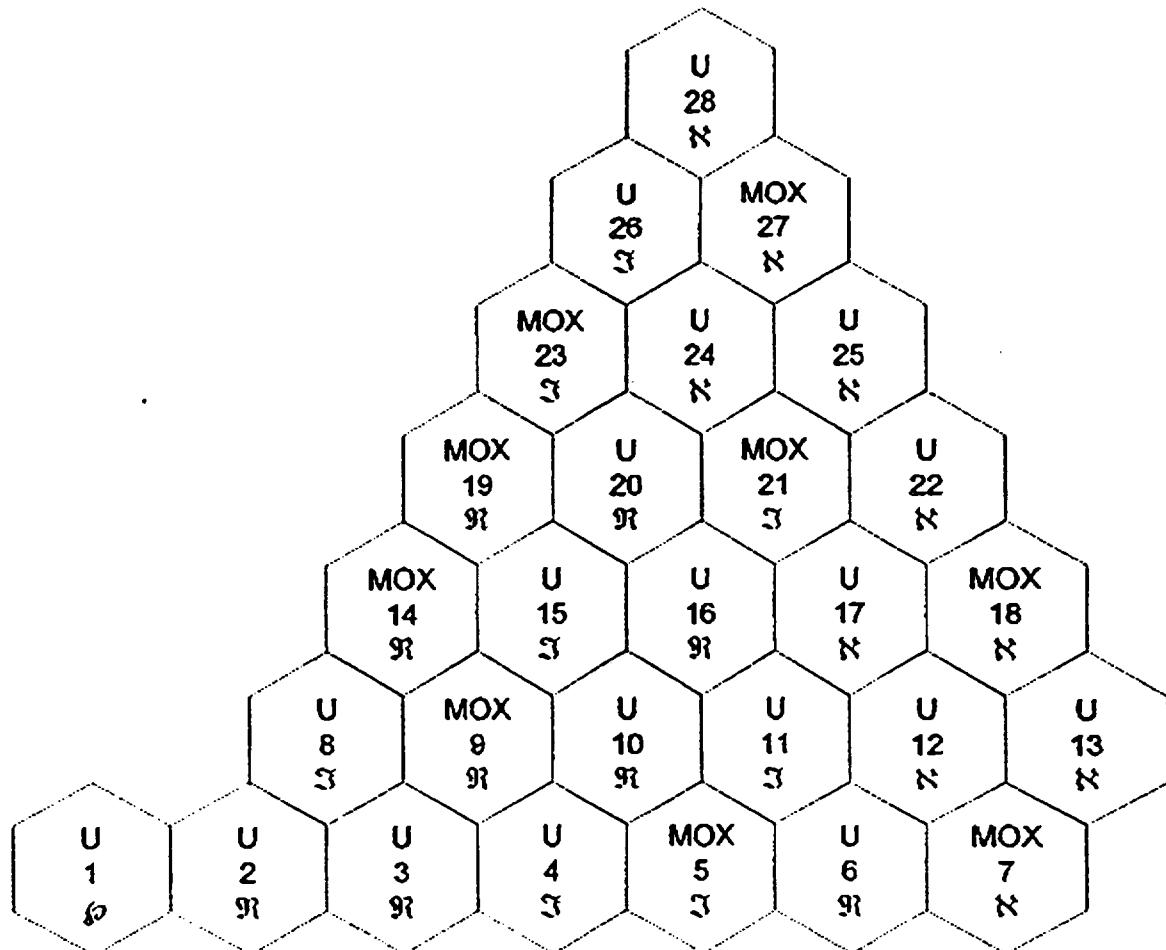
FIG. 1. *Subassembly layout in MOX-fueled reactor (1/6 of WWER 1000 core)*

U : UO₂ subassembly
MOX : MOX subassembly
II : Subassembly position
ℜ : 3rd-year subassembly
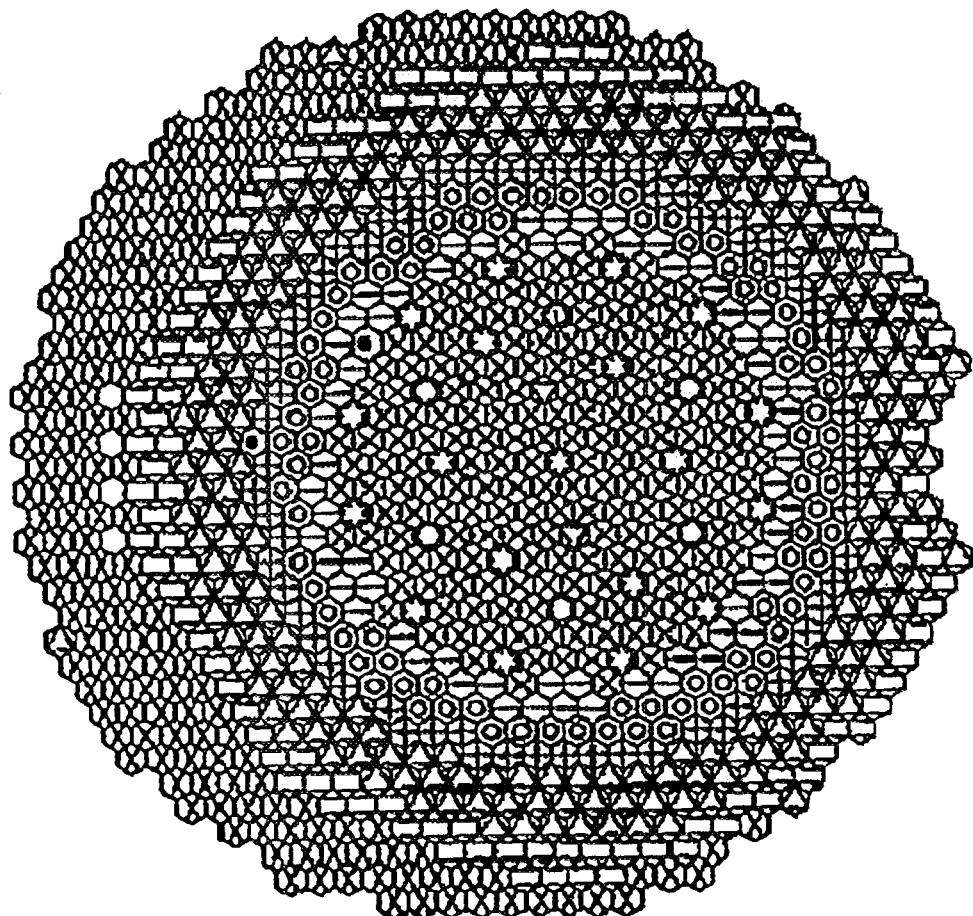
LEZ	17% U5	In-reactor storage	
MEZ	21% U5	Photon-neutron source	
PEZ	20.5% Pu/(U+Pu)	Reactivity compensating rods	
HEZ	26% U5	Scram system rods	
Steel subassemblies		(L-loop scram rod)	
Boron carbide subassemblies		Control rods	

FIG. 2. Layout of the BN-600 reactor hybrid core with steel reflector

The *second process* variant (Figure 4) comprises:

- calcining of plutonium alloy into plutonium oxide
- acid dissolution of plutonium oxide in HNO_3 + Ag(II)
- purification by extraction of plutonium nitrate
- Pu oxalate precipitation and PuO_2 production
- MOX fabrication using the COCA and MIMAS processes.

Neither variant has been adopted to date for lack of sufficient industrial experience; further research and development work will be required in both cases.
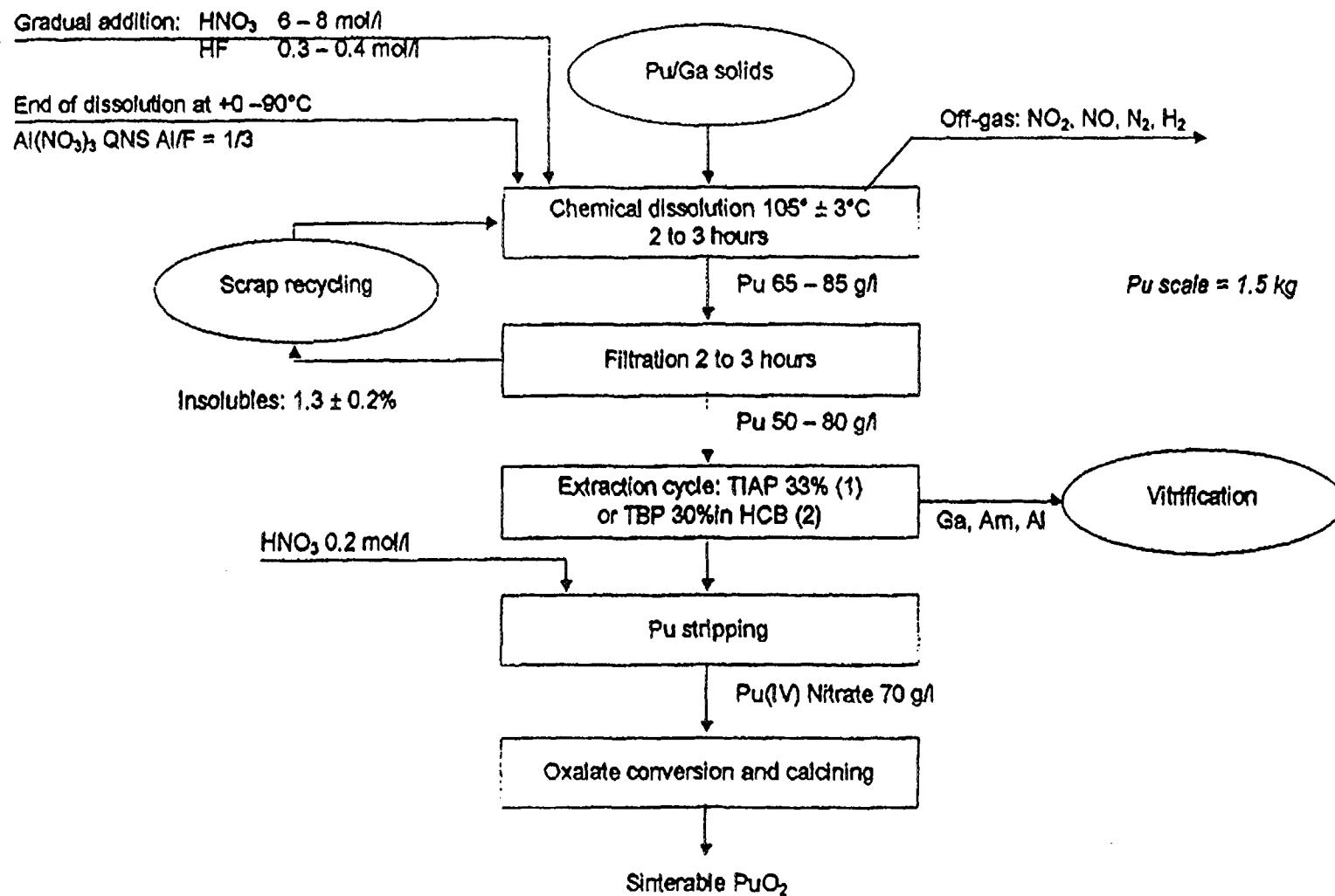
FIG. 3. AIDA/MOX reference flowsheet for converting W-Pu into PuO₂

(1) TIAP: triisoamylphosphate
(2) HCB: hexachlorobutadiene
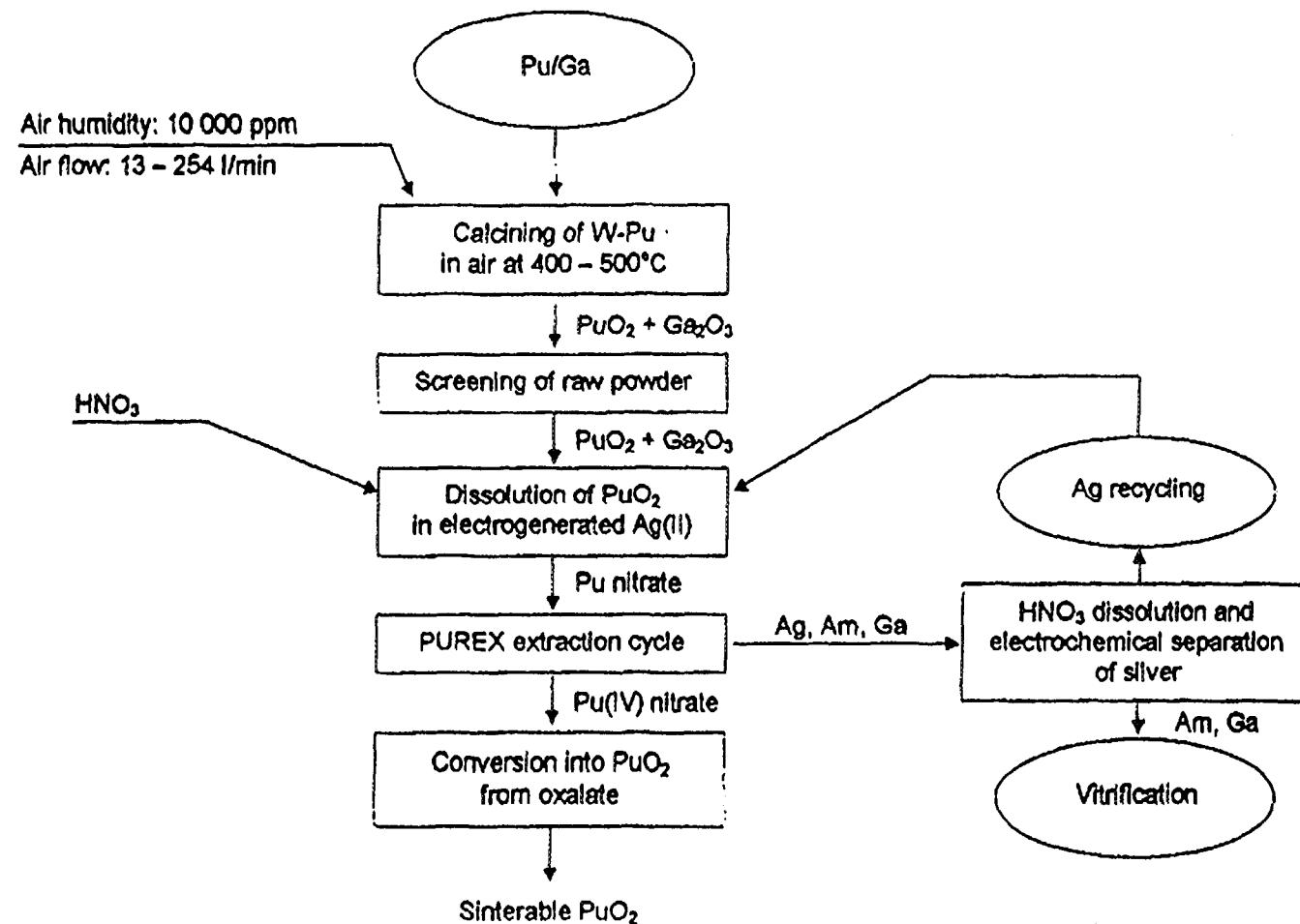
FIG. 4. Variant b of AIDA./MOX reference flowsheet: W-Pu calcining, dissolution, PUREX
extraction, oxalate conversion

4) The capacity of a MOX facility to be built in Russia was determined by the possibility of consuming MOX fuel in existing Russian BN 600 and WWER 1000 reactors. The AIDA/MOX Coordinating Committee initially selected the following Russian reactors:

- BN 600 hybrid core option (=> 240 kg of W-Pu per year), as the first step toward the final objective of 100% MOX fuel in the BN 600 reactor core (1310 kg of W-Pu per year) and gradual removal of all the blankets,

- four WWER 1000 reactors at the Balakovo NPP (=> 4 x 270 kg of W-Pu per year), hence a total capacity of around 1300 kg of W-Pu for the TOMOX 1300 facility, i.e. approximately 30 metric tons of MOX per year.

5) Preliminary design work on the TOMOX 1300 facility implementing glove-box handling technology is underway in Russia with French participation by the CEA, COGEMA and SGN. The results will be available by mid-1997, together with a preliminary estimate of the total cost and itemized cost of the plant components; allowance will be made for the basic facilities already in place at Russian nuclear sites, including Chelyabinsk 65 and Krasnoyarsk 26.

6) A detailed proposal for the TOMOX 1300 plant will be required in 1997-1998 before construction begins in the Russian Federation. The detailed proposal is planned for the AIDA/MOX 2 program stipulated in the proposed Trilateral Agreement between France, Germany and the Russian Federation. The TOMOX 1300 project will be implemented in two separate entities: TOMOX and DEMOX.

- TOMOX plant (transformation of military objects into sinterable weapons-plutonium oxide): Bilateral Cooperation: France-Russia

- DEMOX plant (fabrication of MOX fuel from sinterable W-Pu oxide powder): Trilateral cooperation: France-Germany-Russia (COGEMA-SIEMENS-MINATOM).

4. INTERNATIONAL COOPERATION (Beginning in 1997)

Following the International Workshop in Bonn (May 19-21, 1996) on the dismantling and destruction of nuclear, chemical and conventional weapons, Germany and France decided for greater effectiveness to investigate the possibility of coordinating and integrating their actions with the Russian Federation in the area of dismantling and destruction of nuclear weapons beginning in 1997.

In their final statement, the participants in the Moscow Summit Meeting of April 19-20, 1996 on nuclear safety and security notably requested that a meeting of experts from the G7+1 countries, together with representatives of Belgium, Switzerland, the European Union and the IAEA, be held in Paris in late October 1996 to examine and propose measures for ensuring safe and effective management of military fissile materials identified by their owners as no longer required for defense purposes.

At the experts meeting in Paris (October 28-31, 1996), the German, French and Russian governments issued a joint statement of cooperation for 1997 and 1998, and justified their choice of MOX fuel as the most effective means for eliminating weapons plutonium recovered from nuclear weapons under cost-effective and safe conditions; this cooperation remains open to any country interested in the project, whose pertinence is now universally acknowledged.

This joint action announced by the Germans, French and Russians can thus constitute the groundwork for a broader cooperation mobilizing international financing, both for the construction of

the MOX-fabrication pilot plant (which at the turn of the century could convert 1300 kg of weapons plutonium from dismantled Russian warheads into commercial reactor fuel) and for the equipment modifications that will no doubt prove necessary in the Russian BN 600 and WWER 1000 reactors.

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EXPERIENCE WITH CIVIL PLUTONIUM MANAGEMENT: TECHNOLOGY AND ECONOMICS

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Abstract

Recent NEA work on plutonium has been, essentially, targeted at economic and scientific aspects and the need to identify suitable technical solutions, despite the existing political uncertainties associated with their implementation. Such studies provide the facts and current views concerning plutonium and its civil use; address questions influencing the choice of fuel cycle options and illustrate how economic and logistic assessments of the alternatives could be undertaken. An *ad-hoc* expert group, with a membership drawn from fifteen countries and three international organisations, which was formed in early 1994 under the auspices of the NEA, with the task of identifying, examining and evaluating the broad technical questions related to plutonium management, has just published its work. This paper discusses the work and main conclusions of the expert group and focuses on the following two topics:

❖ Technologies, already implemented, which provide for short and medium–term storage of plutonium or for recycling the plutonium through reactors. A brief review is provided of experience gained with them and technical commentaries are made on their potential future deployment.

❖ Such technologies may, in the longer term, be joined by a further range which are, in some cases, already under development. Attention is drawn to those additional options that may become available.

Another NEA expert group studied in detail the economics of the open and closed fuel cycles and reported, in 1994, its main findings:

❖ Some economic considerations of importance to various aspects of plutonium recycling are also presented in this paper.

1. INTRODUCTION

National policies and programmes concerning the civil use of plutonium are quite diverse, being influenced by a number of complex factors and by different evaluations of the benefits arising from plutonium seen as a quasi-indigenous energy source. The situation regarding plutonium stocks, and plans which are underway to use them, differ from country to country. In some countries, MOX programmes are already actively implemented, in others, though, recycling of separated plutonium is not expected to take place in the short term. There is clearly public interest in the management of this plutonium including any that may become available from non–civil sources.

In recent years the NEA has published reports prepared by international *ad-hoc* expert groups on the economics of the closed and open fuel cycles, on spent fuel management and storage, on the economics and logistics of using plutonium in mixed uranium-plutonium fuel (MOX) and on the physics of plutonium recycling [1, 2, 3, 4, 5, 6, 7]. Additional studies regarding the above mentioned topics are either under way or will be performed in the future.

The increasing quantities of separated civil plutonium and the postponement or the abandonment of plans for fast breeder reactors (FBRs) have resulted in a growing interest, in a number of OECD countries, in recycling plutonium in light-water reactors (LWRs).

To the extent that it is seen as desirable that the option of using plutonium as fuel should be maintained in the future, it should be demonstrated that civil stocks of plutonium would continue to

be managed well in the medium term. In addressing the choice of technologies to be used, it would be valuable to compile and assess:

❖ the availability of and experience in using technology for all segments of the plutonium recycle route and for storing plutonium;

❖ the potential for further improvements in technology, aiming, for example, at even higher standards of environmental protection, safety, worker health and reduced costs; and

❖ priorities for further research and technical developments.

With the above considerations in mind, an international *ad-hoc* expert group — the only one of this kind — was assembled in early 1994, under the auspices of the NEA, with the task of identifying, examining and evaluating the broad technical questions related to plutonium management. Recognising that this was a subject of interest to all countries, whether or not they had in stock separated plutonium or, indeed, any intention of using plutonium, the following nominated participants to the expert group: Australia, Belgium, Canada, France, Germany, Ireland, Italy, Japan, Korea, the Netherlands, Norway, Switzerland, the United Kingdom and the United States. Experts from Russia were invited to participate in the NEA study, in view of their country's accumulated experience with plutonium production, handling and use. The IAEA and the European Commission were also represented.

The expert group was concerned with the technical options for management of civil plutonium, including any that may become available from non–civil uses, but did not consider military plutonium per se. As in previous NEA work on plutonium, institutional aspects, non–proliferation and physical security issues were not addressed. The report of the expert group was published in May 1997 [8].

2. MANAGING PLUTONIUM: EXPERIENCE GAINED

Production and handling of civil plutonium are now into their fourth decade and equipment and systems are at an advanced state in terms of:

❖ quality control;

❖ minimisation of effluents;

❖ minimisation of doses to operators and the public;

❖ radiological and non-radiological safety;

❖ safeguards; and

❖ physical protection.

Safety considerations are of prime importance in the design, construction and operation of plutonium facilities. All such undertakings, which operate in environments that prevent release of alpha–particles, with automated and remotely controlled equipment, are in strict compliance with the conditions of licences issued by the competent authorities. In modern plutonium handling plants, the inventory at all stages of the process is routinely determined from central computers linked to an

array of installed monitors. Some of the monitors are indeed the property of EURATOM and the IAEA who verify the data supplied by the operators.

2.1. Packaging, storage, purification and transportation of plutonium

Civil plutonium production at the major reprocessing facilities in the United Kingdom and France is in the form of dioxide powder which is packaged in stainless steel cans to provide adequate containment, to avoid the possibility of criticality, and to assist in the removal of the decay heat.

Packages of plutonium dioxide are stored within massive concrete cells to ensure protection against major external hazards, such as seismic events and aircraft crashes. The stores are also designed to avoid criticality, and to take account of the release of heat and the physical containment and protection of the plutonium.

Purification of aged plutonium and its recovery from ashes and solid waste are now practised at the industrial scale. The implementation of such operations in the plutonium cycle provides improved flexibility of the overall plutonium management scheme since it would allow for purification of "old" plutonium that has accumulated significant amounts of americium.

Over the past 35 years, separated civil plutonium, in any of its forms (mainly oxide, but also nitrate and, in earlier years, metal), has been safely transported, internally within Europe, Russia and Japan, and internationally from the United Kingdom and France to Japan. Transport by road, rail, air and sea have all been used, under international regulations, within approved transport containers.

2.2. MOX fuel fabrication

Since the earliest days of commercial utilisation of nuclear power, plutonium arising from reprocessing of spent fuel was technically recognised to be best used in FBRs. In the 1950s, the general opinion was, however, that reprocessing capacities in excess of the requirements for feeding FBR prototypes would be available up to a period of 20 years. It was then decided to launch an important R&D programme on MOX fuels which was essentially conducted within the framework of a co-operation agreement between EURATOM and the U.S. Atomic Energy Commission. In the 1960s, interest in plutonium recycle in thermal reactors grew steadily as civil plutonium surpluses appeared unavoidable. As a result, additional countries started R&D activities on MOX fuels: mainly Germany, and to a lesser extent, France, Switzerland, Italy and Sweden for LWRs, as well as Japan for the ATR. The United Kingdom demonstrated MOX utilisation in the Windscale AGR.

MOX fabrication technology was, however, in its infancy during these periods: the main emphasis was placed on simplifying the manufacturing techniques and several alternative processes to pelletizing-sintering were tried out. After the political decision in the United States, in 1976, to defer reprocessing indefinitely, MOX technology was phased out in the United States but continued in:

❖ Germany and Belgium, both for LWR MOX and FBR fuels;

❖ Japan, for ATR and FBR fuels; and

❖ France and the United Kingdom, for FBR fuel.

The industrial MOX manufacturing techniques utilised today were developed during that period, through a trial and error approach, based on the lessons learnt from the demonstration programmes. Meeting the demand of the customers of big modern reprocessing plants (UP2 and UP3 in France and THORP in the United Kingdom) resulted in a rapid expansion of the industrial utilisation of the

MOX fuel which was limited, essentially, by the time required to implement and qualify new fabrication facilities, and by political considerations.

In Belgium, the Belgonucléaire Dessel P0 plant has been operational since 1973 and its earlier fabrication process was used for partial reactor loads and the irradiation supplies for both thermal and fast reactors and facilities. The reference production capacity of the plant is nominally, since its refurbishment in 1985, 35 tonnes HM per year. The CFCa COGEMA plant in France has been processing plutonium fuel since 1962, mainly for FBRs. The capacity of the plant is now being progressively increased to reach 35 tonnes HM per year. During 1995, COGEMA started up industrial MOX fuel production, in its modern 120 tonnes HM per year MELOX plant located at Marcoule. In Japan, the PNC Tokai facilities have produced 144 tonnes MOX fuel in the last 15 years for the fast reactors Monju and Joyo, as well as for the Fugen ATR. The SIEMENS Hanau plant in Germany began operation in 1972 and was shut down in 1991 after a contamination incident. Its capacity during the period 1987 to 1991 was between 20 and 25 tonnes HM of MOX per year for both LWRs and FBRs. Construction of the new Hanau MOX fabrication plant (120 tonnes HM per year) started in 1987. Today, although the plant is 95 per cent completed, SIEMENS and the German utilities have decided not to operate it for political reasons. In the United Kingdom, BNFL and UKAEA have collaborated over the last 30 years in the manufacture of plutonium fuels for a variety of reactors. Recently, BNFL has taken over UKAEA's interest in the collaboration including the development facilities and is currently operating a small–scale manufacturing facility, the MOX Demonstration Facility (MDF) at Sellafield which became operational in 1993 with a design nominal capacity of 8 tonnes HM per year.

Within a period of about 10 years, a total capacity of approximately 400 tonnes HM per year will be available, in reasonably close balance with the total production of the then operating reprocessing plants. Additional MOX fabrication plants are expected to be operational: the Belgonucléaire Dessel P1 plant (40 t HM/y); the BNFL SMP plant (120 t HM/y); the MELOX extension (50 t HM/y) and the Japanese MOX plant (about 100 t HM/y).

New MOX fabrication plants offer better protection against earthquake, aircraft crash, pressure wave and fire. They have larger flexibility in terms of fuel designs as well as in terms of fabrication campaign sizes. Extensive process automation or remote control of operation has been introduced to cope with the use of plutonium arising from the reprocessing of high burn–up spent UO_2 fuel, and the manufacture of MOX fuel designed for increased discharge burn-up.

In Russia, efforts have been essentially focused on the development of MOX fuel for fast breeder reactors. Initially, in 1957, a core of a metallic alloy was fabricated for the pulsing fast reactor IBR-30. Starting in 1959, MOX fuel was made, first for the BR-5 and IBR-2 reactors, and later, from the mid-1970s, for the BOR–60 and for experimental sub-assemblies tested in the BN–350 and BN–600 reactors. Two technologies are being developed to process plutonium into MOX fuel: pelletizing and vibrocompacting. They are implemented at Mayak, Chelyabinsk and at RIAR, Dimitrovgrad, respectively. As a consequence of the delay of the construction of three to four units of the BN–800 fast power reactor type, construction of a MOX fuel fabrication plant, called COMPLEX–300, is currently suspended.

Given the characteristics of plutonium of low irradiated fuels (reduced alpha activity and neutron flux, low [241]Am built-up and a significant decrease of the gamma irradiation level) as compared with plutonium commonly known as reactor–grade, the technologies currently involved in the MOX fabrication plants may be easily adapted to the fabrication of MOX fuel with such plutonium. The MOX option for the disposition of such plutonium could effectively benefit from the experience gained in Europe for further reductions in development and licensing costs, and time.

2.3. Plutonium use in reactors

The physical characteristics of plutonium and uranium-fuelled reactors are only slightly different and plutonium recycling is possible in most of the current LWRs (PWRs or BWRs). MOX fuel, however, cannot substitute for uranium oxide fuel without some relevant precautions which are necessary to cope with a reduction of the absorber efficiency, a smaller loss of reactivity during the exposure and a modification of the power distribution at the boundary between MOX and UO_2 assemblies. From a practical point of view it is possible to deal with such consequences without major problems. The reactor's control and safety characteristics are dependent on the utilised MOX ratio. If the share of the MOX fuel in the core is low (less than 50 per cent, as is the case today), it is generally easy to adapt existing reactors to the use of MOX fuels. This ratio could be increased up to 100 per cent by the use of specifically designed and licensed reactors or, in some cases, by modifying the control rod systems of existing reactors. Concerning MOX fuel failures, the failure characteristics and the activity releases are very similar to those of uranium oxide fuel.

In Germany, after the early plutonium recycling programmes in BWRs (Kahl, KRB-A), the beginning of commercial MOX use in LWRs was concentrated in PWRs. The three KONVOI PWRs in Germany are licensed for the irradiation of up to 50 per cent MOX fuel assemblies of the type 18x18 and several BWRs have requested a MOX insertion licence or have already received such a licence, e.g. KRB-B. Experience also exists in Switzerland with MOX loaded both in the Beznau–1 and Beznau-2 plants. The French programme regarding the 900 MWe PWRs of EDF started with a first reload including 16 MOX fuel assemblies in 1987 at St. Laurent–B1 and comprises, at present, nine plants. Seven additional 900 MWe PWRs of EDF are licensed to recycle plutonium. In Belgium, after the 1963–1987 data base acquisition programme in the BR3 PWR (with up to 70 per cent MOX in a reload), two 900 MWe PWRs have been loaded with MOX fuel since 1995. Lastly, in Japan test MOX fuel assemblies have been loaded in the Tsuruga–1 (BWR) and the Mihama-1 (PWR) which are both commercially operated reactors. It is expected that MOX recycling, on an industrial scale, will commence in the near future in Japan.

The experience accumulated up to now with MOX fuel recycling and the different strategies aimed at increasing the use of plutonium in MOX fuel in PWRs and BWRs, leads to the conclusion that MOX fuel can be considered an industrial product, like uranium fuel. However, as is normal for every industrial product, future possibilities are discernible for improving MOX fuel in order to gain more efficiency and reactivity.

For countries and utilities involved in fuel recycling, the following main trends could be observed:

❖ Continuation with MOX recycling on a broad industrial basis in Europe and Japan. Currently, 32 LWRs are licensed to use MOX fuel. Beyond the year 2000 it is expected that additional reactors would use MOX fuel in these countries.

❖ Improvement of fuel utilisation by multi–recycling strategies.

❖ Increasing burn–ups by using new MOX fuel assembly designs with higher plutonium contents and higher percentage of MOX assemblies in the cores.

❖ Stronger efforts towards standardisation in order to improve economics.

Several fast breeder reactors (e.g. Phénix, Superphénix, PFR, BN-600, Monju) have been in operation for many years in a number of countries. The design, construction and operation of such plants and their related MOX fuel manufacturing facilities have provided extensive experience of

more than 200 reactor–years as a basis for engineering further improvements. Experience has also been gained in Japan with the prototype Advanced Thermal Reactor Fugen (a heavy-water moderated, light-water cooled, pressure tube type reactor of 165 MWe), which is characterised by the capability to utilise plutonium both flexibly and efficiently.

3. ECONOMIC CONSIDERATIONS

The economics and the related logistics of plutonium recycling have been well studied over the years [1, 2, 5]. It is understood that other plutonium management methods which are currently under investigation have large associated economic uncertainties.

In early 1991, an expert group with a membership drawn from fourteen countries and four international organisations was formed by the NEA to examine the economics of the nuclear fuel cycle with particular reference to costs associated with a large modern pressurised water reactor commissioning in the year 2000. The expert group published its report in July 1994 [2]. That report, being the only reference work in this area, has been heavily quoted, translated in other languages, it has also been widely discussed and scrutinised.

The primary task of the expert group was to update the earlier NEA study which was published in 1985 [1]. That earlier study analysed the fuel cycle cost using internationally accepted, investment appraisal methodology.

Two back-end options were considered in the study. The first was based on prompt reprocessing of the spent fuel. The basic cost estimates used were supplied by BNFL in conjunction with COGEMA. These estimates assumed that the fuel would be reprocessed in a newly constructed plant. In costing this plant the experience gained from the design, construction and operation of the latest reprocessing plants of THORP at Sellafield and UP3 at La Hague has been taken into consideration. The second option was based on long–term storage followed by direct disposal. Cost estimates developed by the SKB company in Sweden were used as the reference case.

The expert group concluded that levelised lifetime fuel cycle costs have been reduced, by 40 per cent, since the 1985 NEA study. Resulting reference discounted costs were 6.23 mills/kWh for the reprocessing option and 5.46 mills/kWh for the direct disposal option. In overall fuel cycle cost terms, the direct disposal option remained at about 10 per cent lower than the reprocessing option, based on the reference cases studied. However, in the light of the underlying cost uncertainties, that small cost difference was considered to be insignificant and, in any event, represented a negligible difference in overall generating cost terms. Given that fuel cycle costs are very strongly country dependent, it is likely that considerations of national energy strategy including reactor type, environmental impact, balance of payments and public acceptability would play a more important role in deciding a fuel cycle policy than the small economic difference identified.

Concerning plutonium separation, handling and use, some of the economic parameters considered by the expert group are briefly discussed below.

Although reliable commercial MOX fuel fabrication cost data are, in general, lacking, it is known that they are higher than those of enriched uranium oxide fuels. This is due to the higher investment cost of a MOX plant and to the latter's modular nature which does not confer the same advantages of scale that apply to a uranium plant. As the use of MOX fuel increases and the new MOX fabrication plants reach higher commercial throughputs, the present MOX fabrication prices will fall. The industry expects that, on current plans, the MOX fabrication price will have fallen to about three times that for uranium fuel by 2010. However, the reference case in the 1989 NEA Plutonium Fuel study [5] assumed that by the late 1990s, MOX fabrication prices would be four times those for enriched uranium fuel. For the purpose of the 1994 NEA Economics study, it was

agreed that the reference case would prudently use a ratio of four over the entire reactor lifetime. Thus, the reference price was set at $1 100 per kg HM, with a corresponding range for sensitivity studies of $800 to $1 400 per kg HM. This range corresponded to the use of fabrication price ratios of three and five, respectively. It also corresponded to the use of the low and high uranium fuel fabrication prices ($200 and $350 per kg U, respectively), which were adopted by the expert group, with the reference MOX fabrication factor of four. The prices used in the study were considered to be very robust. Depending on the study's costs of uranium purchase and enrichment, as well as on the MOX fabrication prices used, a range of plutonium credit values of $-10.0 to $17.0 per g of fissile plutonium were obtained. The reference credit value was $5.0 per g of fissile plutonium.

Published costs of plutonium storage vary widely owing to differences in the size of stores and the economic and financial differences which exist between countries. They are usually taken to be in the region of $1 to $2 per g of total plutonium, Pu(t), per year. Some countries requiring longer-term storage are incurring additional prices of this order. Reprocessing companies include the cost of short–term storage as a minor component of the overall reprocessing price.

As noted above, long–stored plutonium may need to be purified, by the removal of in–grown americium before it can be recycled. The extent to which this will be necessary will depend upon the source of the plutonium, its period of storage and the design of the MOX fuel fabrication plant. The cost may vary [5] between $10 and $28 per g Pu(t); a price of $18 per g Pu(t) would be appropriate for plants treating about two tonnes Pu(t) per annum. This figure relates to americium removal from plutonium oxide; it would be less if the plutonium could be stored as a nitrate solution.

If plutonium transport is needed, the price would be far higher per kg than that of spent fuel due to the more onerous criticality and physical security requirements. Indicative figures of around $500 to $900 per kg, which will vary with the mode of transport (air, land or sea) have been published [5]. Plutonium transport costs within a single site would be trivial by comparison.

Lastly, the expert group adopted the view that the strong likelihood of economies arising from technological developments and commercial pressures would make any upward movement of reprocessing prices highly unlikely in the future.

4. FUTURE OPTIONS UNDER DEVELOPMENT

The future utilisation of plutonium will critically depend, among other factors, on the evolution of nuclear policies. The NEA expert group addressed plutonium burning in fast and other reactor systems, as well as geological disposal of plutonium. Such technologies, which are currently under research and development, would need to be fully demonstrated and accepted.

4.1. Studies concerning currently available reactor concepts

There are various important R&D activities going on in many countries regarding the utilisation of reactors, currently used for power generation, in managing present and future plutonium inventories. As designed, a fast breeder reactor produces more plutonium than it burns, but, at the conceptual stage, it is possible to transform it into a burner if reducing the plutonium inventories is needed, whether the plutonium originates from power reactors or from ex–civil uses. Similar concepts can also apply to both CANDU reactors and PWRs.

In France, the CAPRA project has been launched to demonstrate the feasibility of a plutonium-burner fast reactor core compatible with the European Fast Reactor (EFR) technology. Similar studies have also been carried out in Japan. The R&D programme in support of this activity is complemented by various international collaborations with Japan, Russia, Switzerland and Italy.

In Japan, conceptual studies have been carried out on the modification of high conversion PWRs to reduce surplus plutonium and on a new concept for the LWR fuel matrix which can become chemically stable during irradiation, hence capable of being disposed of without further processing.

Although CANDU reactors have not up to now been fuelled with MOX fuel, they have been operating with natural uranium in which fissile plutonium is the largest contributor to energy production. This feature is a result of the high conversion ratio of the natural uranium — heavy-water lattice. Over 200 reactor-years of operation demonstrate the ability of existing CANDU plants to burn plutonium-bearing fuels.

4.2. Advanced concepts

Concerning the longer term, very efficient, reliable and safe fast breeder systems could be envisaged to extract all the fissile energy from the stockpile of depleted uranium which would have been accumulated over the years throughout the world. These systems may incorporate modular and integral type reactors with metal, nitride or carbide fuel. They could operate with equilibrium fuel cycles using the uranium stockpile without increasing the overall TRU inventory and minimising, in this way, the waste and TRU generation per unit of energy produced.

High temperature gas-cooled reactor (HTGR) options which would burn plutonium to the point of almost not requiring reprocessing are also being considered. Pebble bed type HTGRs using plutonium balls (to burn plutonium) and fertile balls (thorium or ^{238}U to breed) can offer almost 100 per cent plutonium burning because a continuous supply of fresh plutonium balls would compensate reactivity partially lost to maintain reactor operation.

In the far future, new reactor concepts like molten salt reactors might become more attractive for plutonium and minor actinide burning.

Other concepts relate to certain rock-like LWR fuels, consisting of mineral-like compounds, which are, chemically and thermodynamically, so stable that they are not soluble in nitric acid in normal ways. During irradiation in reactors, most of the solid fission products would be solidified by their substitution in the matrix compounds and/or precipitated as new mineral-like compounds in the fuels. The phases thus obtained in the spent fuels would become stable for geological periods. Accordingly, they would be suitable for direct disposal without further processing.

4.3. Geological disposal of separated plutonium

Should it be decided by national policies not to use plutonium as a fissile resource, stocks may in future be conditioned in a form compatible with regulatory requirements for final disposal.

A thorough evaluation of the issues associated with the management and disposition of plutonium, concentrating primarily on weapons plutonium, but also considering civil plutonium, was completed in 1994 [9] by the Committee on International Security and Arms Control of the U.S. National Academy of Sciences (NAS). The NEA expert group reviewed the conclusions of that committee regarding a number of feasible disposition options which should be so designed to place the excess plutonium in a physical form that is at least as inaccessible for future weapons use as the plutonium in spent fuel from civil nuclear reactors. After the completion of the work of the NEA expert group, the U.S. Department of Energy published a Technical Summary Report for Surplus Weapons–Usable Plutonium Disposition [10].

The disposal options reviewed included both vitrification and burial in deep boreholes, as recommended in the NAS study. Also treated were variants of the vitrification option that have recently been identified as having promise: both involve the immobilisation of plutonium in ceramic or metallic forms together with fission products. The vitrification option and its variants would all yield a product that is self–protecting and resistant to retrieval of the plutonium, rendering it virtually

as inaccessible as in spent nuclear fuel. The ultimate waste form would be disposed in a mined geologic repository.

Laboratory experiments have produced experimental glasses with 7 to 15 wt. per cent plutonium, but these glasses have not yet been fully characterised, so that their performance over long times in a repository is not known. In addition, most plutonium disposition options generate one or more high–level radioactive waste streams which are not included in the current plans for the existing high–level waste geological repository programmes of most countries. Disposition of plutonium in a geological repository raises a new set of issues and potential impacts. The severity of these impacts depends on both the nature of the plutonium waste forms considered and on the baseline design of the repository. Waste forms differing from those currently expected would have significant impacts on the waste management system.

Facility impacts could include safeguards, radiation and thermal output, required capacity and public perception. Design and operational impacts could result from safeguards requirements, physical or chemical attributes of the wastes and thermal and radiation output.

In summary, there are a variety of options for plutonium disposition which would result in geologic disposition of unique wastes. Such techniques will require additional research and development prior to implementation. Suitability and performance of these wastes must be assessed against the particular requirements of the disposal facility for which they are destined.

5. CONCLUSIONS

Quantities of separated plutonium, which have a variety of isotopic compositions, have been increasing over the past three decades and are expected to continue to increase during the next few years. Although the evolution of plutonium inventories over the coming decades is subject to significant uncertainties, successful implementation of mixed uranium-plutonium oxide recycling programmes, which are under way in a number of countries, would result in an equilibrium between plutonium production and consumption and would eventually reduce civil plutonium stocks.

The NEA expert group concluded that in the next 15 to 20 years:

❖ In a number of OECD countries, a significant part of the separated plutonium will be recycled as MOX in thermal reactors. The technology for thermal recycling is already in use without problems, and is properly safeguarded. The temporary plutonium accumulation will need to continue to be stored and some will need to be purified in order to have the internally arising americium removed before recycling. The addition and expansion of existing industrial capacities will enable the reduction of stocks to the level required for the efficient operation of the facilities.

❖ Existing technologies for storage and recycling developed in the civil fuel cycle can cope, if necessary, with surplus material produced from non-civil sources.

In the longer term, depending on the evolution of nuclear policies, the following alternatives (alone or in combination) may be considered:

❖ A continuation of the current management techniques, as quoted above.

❖ Plutonium burning in fast neutron reactors and other dedicated reactors, including thermal reactors.

❖ Conditioning plutonium in a form compatible with regulatory requirements for final disposal.

Such long–term technologies would still have to be fully demonstrated through continuous research and development efforts.

In summary, the management of separated plutonium presents no major technical difficulties, but is a matter of carefully applying existing technology to the minimisation of any plutonium stocks. Nevertheless, a number of complex and interrelated non–technical factors, which have not been addressed by the NEA expert group, such as considerations of national and international policy concerns: non-proliferation, public acceptability, economics, environmental impact and infrastructure, would inevitably play a central role in thoroughly developing, implementing and completing the technical options examined.

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SESSION III

DEVELOPMENT POTENTIAL FOR THERMAL REACTORS AND THEIR FUEL CYCLES

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Abstract

Water-cooled reactors represent the only types which have reached widespread commercial use up to the present day. Given the plentiful supply of uranium in the world today, this situation might be expected to continue for some time into the future. Nevertheless, for different reasons several countries consider that either new reactor types should be developed or that existing types should be improved substantially. The predominant reason in the short term is to improve the competitive position of nuclear energy supply versus fossil energy. In the longer term, regional and national fuel supply independence may become the dominant driving forces. This paper outlines several possible means for responding to these driving forces. It is not meant to include an exhaustive list of all possibilities, but only to illustrate some alternative routes. These routes range from enhancement of existing reactor concepts to combination of nuclear with fossil systems, and finally to the introduction of radically new thermal reactor concepts. Each of these has its obvious advantages and disadvantages and will come forward or will recede depending on technical feasibility, economics, long-term sustainability, and national policy.

1. INTRODUCTION

Key Issue Paper No. 3 in this Session describes the likely evolution of the world's nuclear power system in the period 2015 to 2050, and reviews the factors which might influence that evolution in one direction or the other [1]. The Key Issues Paper was necessarily constrained in the scope of reactor alternatives which could be proposed; a thorough investigation of all possible reactor and fuel cycle strategies obviously is impossible within the time span of this Symposium.

This paper addresses one specific aspect of the possible evolution of nuclear power. Thermal reactors are now, and will remain for some time, the dominant contributor to the world's "fleet" of electricity producers. The central question is whether or not these systems have reached an evolutionary 'plateau' beyond which their benefits to society can improve only marginally and incrementally in the future. It is the role of this paper to investigate that central question.

2. SCOPE OF THE PAPER

This subject is by its very nature speculative; discussion of a particular improvement option implies no warranty as to whether that option will be developed in practice. The goal of the paper is to present some current research topics in the areas particular to thermal reactors as they are being carried out today, and the ways in which design improvements might impact nuclear station and fuel cycle economics, fuel performance, safety, etc. if and when the improvements were introduced in the time period from 2015 to 2050. It is a further condition of the paper scope that improvements which likely will be implemented earlier than about 2015 are not discussed here.

2.1. Potential Improvements

It is a basic assumption of this paper that the predominant factors which should be influenced favorably in the further development of thermal reactors are:

(a)   utilization of natural resources and national capabilities,
(b)   economic benefits to society,
(c)   overall environmental impact,
(d)   demonstration of facilities' safety,
(e)   government and public approval of the enterprise,
(f)   national and international policies and goals,
(g)   energy supply sustainability.

The development programs discussed below are examples of those being undertaken in a number of countries with the aim of contributing to one or more of these factors, which are taken from Chapter 2 of Key Issues paper No. 3 [1].

2.2. Long Term Thermal Reactor Improvement Concepts

2.2.1. Combined NPP and Gas Turbine Thermal Cycle

Nuclear power competitiveness is in doubt in several countries. Combined cycle gas turbines (CCGT) are very competitive for base-load electricity generation, if natural gas is available at low prices. With relatively low capital costs and natural gas prices in the range of 2.9 to 4.7 US$/GJ, the total unit energy cost would be in the range of 29 to 45 mills/kWh (1 mill = 10^{-3} US$) at 10% real interest rate[2]. Nuclear power plants can produce electricity at 36 mills/kWh if the overnight capital cost is around 1350 US$/kWe at the same real interest rate, assuming low operation and maintenance (O&M), fuel-cycle and back-end costs.

Strong efforts are being made to reduce capital costs and construction times; CANDU, AP-600 and ABWR are well-known examples of these efforts. However, these reactors still have the limitations of the steam Rankine cycle and the same materials used in current commercial NPPs (PWR, BWR and CANDU plants). These limitations fix an upper limit of about 35% to thermal efficiency of electrical generation.

The economic comparison can be made in terms of cost per thermal kWh rather than electrical kWh. On this basis, the CCGT produces energy in the range of 15 to 24 mills/kWh(th) while the NPP achieves 12 mills/kWh(th). It can be seen that the NPP produces thermal energy more cheaply than the CCGT but loses this advantage in the conversion of the thermal energy to electrical energy. Some designers address this issue by changing the fuel, coolant, moderator or primary configuration (Super-critical LWR, HTGR, LMR). These designs achieve higher thermal efficiencies at the expense of present commercial experience.

As experience with commercial water-reactor technology has been very successful, achieving higher thermal efficiencies by building on current NPP technology seems an attractive approach.

Using hot exhaust gases from a conventional gas turbine to increase the outlet temperature from the steam generators in an NPP has been recently studied in a number of countries, including Argentina[3],[4]. This cycle can be called dual (two different energy sources) and combined (two different energy conversion systems). Some issues need to be analyzed to achieve a better understanding of this option.

The combination of CCGT plus NPP produces a completely new generation system with a total unit energy cost lower than either a CCGT or an NPP alone. The total overnight unit capital cost is significantly lower than that for an NPP and slightly higher than those for a CCGT, while the unit fuel-cycle cost is slightly higher than that for an NPP and significantly lower than that for a CCGT.

2.2.1.1. Example of a Small Dual Combined NPP and GT[5]

Commercial gas turbines are simple and small, unlike commercial NPPs. Current gas turbine power outputs do not exceed 250 MWe. Thus, a compatible reactor for use with present gas turbine technology is a small and simple PWR design, with projected costs as close as possible to those of current NPP generation costs.

An Integral PWR (IPWR) design, self-pressurized and cooled by natural convection is the simplest PWR design that could be evaluated. For this technology, 150 MWe can be taken as the practical size limit, with larger sizes adversely affected by complex feed-back effects. An available design of a 141 MWe IPWR is assumed for the NPP in a dual-combined cycle. For such a plant operating alone, the unit capital cost would be 15% higher than that of a current advanced design large PWR and the unit fuel-cycle and O&M costs would be higher than those of the large PWR due to the low power output and greater core leakage. Thus, the total unit energy cost would be about 20% higher than that of the large PWR.

Of several possible gas turbine designs that could be used, the Siemens V94.2 design was chosen, with an output of 151 MWe at 35% efficiency. This turbine is that used in the Siemens GUD 94.2 CCGT power plant. With an exhaust temperature of 540°C, the steam temperature from the IPWR could be raised from 280°C to 510°C. With this temperature increase, the power output from the steam cycle would increase from 147 MWe to 228 MWe, giving a power output from the whole plant of 379 MWe at an efficiency of 44% (with 56% efficiency for the nuclear-steam cycle).

An economic comparison of the dual-combined plant with a CCGT and the NPP alone was made based on a capital cost of the dual-combined plant of 840 US$/kWe, a natural gas cost of 1.8 US$/GJ and a real interest rate of 10% per year. The resulting levelized unit energy costs (LUEC) are about 28 mills/kWh for the dual-combined plant compared to about 38 mills/kWh for the NPP alone and about 30 mills/kWh for the CCGT plant.

2.2.1.2. Example of a Large NPP and a GT

In a dual-combined cycle, several advantages of a large NPP are reduced compared to a small NPP (100 to 300 MWe, according to the IAEA), considering current GT technology. For a large NPP, the size of the heat exchanger (HX) to raise the steam temperature could be a technological limit. Considering the compensating trends of fuel and capital costs, lower steam temperatures could be used without a significant economic penalty. The lower steam temperatures would increase the log mean temperature difference (LMTD) between the exhaust gas and the steam and thus reduce HX size.

For a 700 MWe PHWR reactor, similar to the Atucha II reactor now under construction in Argentina, because of the large investment required (700 to 1200 million US$) and the low price of

electricity in the market, the return interest rate (RIR) is 2% to 6% per year[6], making it difficult for a private utility to build.

By adding two Siemens V94.3 (222 MWe) gas turbines at the reactor site and increasing the steam generator outlet temperature from 271°C to 450°C, the power output of the whole plant increases from 700 MWe to about 1550 MWe, more than doubling the original power, for about 200 to 300 million US$ additional investment. The reduction of the steam outlet temperature from 540°C, as in the previous example, to 450°C results in the size of the HX being about one-third the value it would otherwise have, reducing its cost substantially. The dual-combined project would increase the RIR to a more attractive 12% to 15% a year.

2.2.2. Heavy Water Reactors

This section of the paper considers mainly the potential for advanced development of the CANDU-PHWR in the long term. The key characteristics of the CANDU design that underlie its current performance and future potential are:

(a)   Heavy Water Moderator Separate from the Coolant
(b)   Horizontal Fuel Channels in Pressure Tubes
(c)   On-Power Fuelling with Short Fuel Bundles

These features will be maintained in future designs, whatever other modifications are made, to capitalize on the benefits arising from their use as well as to continue to benefit from the large investments in the various technologies involved.

2.2.2.1. Fuel Cycles

There are several options available for the use of advanced fuel cycles in CANDU reactors to provide increased fuel burnup, lower fuelling cost, better resource utilization and simplified waste management [7,8,9,10]. Some of these options are expected to be implemented in the medium term, with their benefits enhanced by the use of an improved fuel bundle design, the CANFLEX bundle, developed jointly in Canada and Korea.

Other fuel-cycle options for the CANDU could be available in the longer term. The use of thorium in PHWR reactors has been under consideration since the early 1960s to take advantage of the significant thorium resources in the world. Options being studied include once-through cycles burning slightly enriched uranium (SEU, 1.2% U-235) oxide and thorium oxide in separate channels, with the U-233 formed from thorium being burned in situ, and reprocessing cycles in which mixtures of ThO_2 and enriched UO_2 or PuO_2 are used as fuel [7]. A non-reprocessing option is the use of natural uranium with thorium, but to maintain reactivity the thorium inventory would be limited to about 20% of the core with current core designs [9]. In addition to reactor physics studies, AECL is undertaking thorium fuel fabrication development and irradiation testing of thorium fuels. CANDU reactors can utilize thorium fuels with essentially no design modifications. Fuel management presents a challenge in once-through thorium cycles, but the on-power fuelling of the CANDU reactor provides flexibility in this area.

Eventually, taking advantage of the high value of thermal utilization for thorium in a thermal-neutron flux and reducing even further the low parasitic neutron absorption in a current CANDU core design, a self-sufficient thorium cycle (SSTC) should be possible, which would require no further uranium or plutonium make-up [9].

Synergistic use of the CANDU with the liquid-metal fast breeder reactor (LMFR) is also possible in the longer term to improve fuel supplies. In a CANDU-FBR synergy, a small number of

120

efficient LMFRs could provide the fissile material for a larger number of existing lower-cost CANDU reactors. About eight or nine CANDU units could be supplied by one LMFBR [8].

2.2.2.2. Passive Safety Features

There is a world-wide trend to greater use of passive safety features in nuclear power reactors. Current CANDU designs rely on a mix of active and passive features to ensure safety. Current CANDU reactors also incorporate certain features for operational purposes that provide, in addition, inherent safety characteristics [11,12]. These features will be maintained in future CANDU reactors.

Future CANDU designs will provide enhanced safety by incorporating new passive features [13] or by replacing active elements by passive elements in certain safety systems. These safety enhancements include:

(a)   a simplified emergency coolant injection system with additional passive features
(b)   passive heat removal from the moderator
(c)   passive cooling of the shield-tank water
(d)   passive cooling of the containment atmosphere under accident conditions, utilizing natural circulation of the steam-air mixture, elevated emergency water storage tanks and gravity-driven heat removal in elevated condensers
(e)   self-starting hydrogen recombiners using a developed wet-proof catalyst, located to assist natural convection in the containment under accident conditions.

Some of these features will improve reactor economics as well as enhance safety. For example, the simplified emergency coolant injection system will reduce the number of valves considerably and simplify their design. Also, passive heat removal from the moderator will allow higher moderator temperatures which permit recovery of this heat for useful purposes.

It is expected that such features will be introduced into CANDU nuclear power plants before 2015 and that they will be standard after that date.

2.2.2.3. Next Generation CANDU-PHWR Designs

AECL has established cost reduction targets for both operating and capital costs of CANDU reactors. Operating cost reductions, with a target of 25% in the short term, will be accomplished mainly by the use of advanced fuel cycles, although some will be achieved by design modifications. However, achievement of the long-term cost reduction targets established by AECL, 50% for both operating and capital costs, will require significant design changes. These changes can be achieved while retaining the essential good characteristics of present designs discussed above.

The first major change would be introduction of a modified fuel channel with the pressure tube in contact with the cool heavy water moderator, a solid insulating annulus with a thin fuel guide sleeve on its inner surface [14]. This would permit the use of a much higher coolant temperature (and pressure, if required) to increase the thermal conversion efficiency.

`A change of coolant was considered in order to achieve high temperatures. Candidate coolants evaluated were hydrocarbons, fluorocarbons, N_2O_4, liquid metals, molten salts and gases; all had certain drawbacks. The focus at this time is on water at supercritical pressures and temperatures; heavy water in the shorter term and light water in the long term.

Supercritical water is attractive because steam turbines are available for it essentially off the shelf, with four modern fossil units in operation and another 14 units under construction around the world. Thermodynamic efficiencies approaching 50% are being realized.

121

For CANDU, at a supercritical pressure of 25 MPa, two stages are envisaged at coolant core-mean temperatures of 400°C [15] and 500 ° C. With heavy water coolant and a core-mean temperature of 400 ° C, a conventional indirect cycle would be employed with heat transferred to a secondary light-water system providing superheated steam at 19 MPa and 400 ° C to the turbine. A unit cost reduction of about 20% would result from efficiency improvement. Additional benefits would be reduced in-core density, providing lower void reactivity, reduced heavy-water inventory and cost, higher specific heat, providing lower mass flow and pumping power, and high heat transfer coefficients, providing a good chance of achieving acceptable performance with conventional zirconium alloy fuel cladding.

For coolant core-mean temperatures approaching 500 ° C, unit cost reduction would approach 30% from efficiency improvement and void reactivity would be further reduced, although reduced coolant density and specific heat would result in increased flow rate and pumping power. Zirconium alloy fuel cladding would no longer be satisfactory because of increased corrosion rates. Chromium plating and SiC cladding [16] of the fuel are being examined. With heavy water precluded from use in the turbine-condenser system, the plant could operate on an indirect cycle with heavy water primary and light water secondary or with light water for both, or a direct cycle with light water.

2.2.2.4. Advanced Heavy Water Reactor

An advanced heavy water reactor (AHWR) is under development in India. This novel reactor design would utilize mixed oxides of thorium and U-233 in a natural extension of the once-through thorium concept incorporating reprocessing and refabrication. The design will be of the vertical-channel pressure tube type and cooling will be by boiling light water. The U-233 enrichment in the thorium will be such that the system will be self-sustaining in U-233. This will require driver (seed) zones in the core with channels fuelled by mixed oxides of uranium and plutonium. In this design, the composite core will have a negative void coefficient of reactivity and will be cooled by natural convection. The design will include other passive safety features including core-flooding in the event of an accident.

2.2.3. Light Water Reactors

2.2.3.1. Next Generation LWRs

The primary objective of current R&D activities for the improvement of LWRs is to improve economics in order to ensure that they will be able to stay competitive in the power supply market since nuclear power is expected to contribute strongly to the suppression of fossil fuel consumption and thus to the protection of the global environment [17]. Needless to say, these activities take into account the persistent public uneasiness about the safety of nuclear plants in the safety design, including prevention as well as mitigation of severe accidents. The major strategy to attain this objective is simplification: utilization of large fuel bundles and a shroud-less core and other evolutionary ideas are under consideration in the design of the Improved Evolutionary Reactor (IER), a next generation ABWR [18], and an optimal combination of active and passive safety systems and the use of horizontal steam generators, in the case of the APWR [19]. A simplified 1200Mwe PWR also is being explored as an evolution of the AP-600 [20]. All these candidates for the next generation LWR are expected to be able to accept cores of 50% to 100% MOX for providing utilities with a wide range of fuel cycle flexibility and opening up the choice for an optimized back-end strategy in terms of disposal costs. The target burnup is set at around 60,000MWd/t for a UO2 core and 45,000MWd/t for a MOX core [21][22].

2.2.3.2. Achieving Higher Conversion Ratios

A more innovative idea under preliminary consideration is to pursue a core with a higher conversion ratio. Since two-phase flow heat transfer in the BWR is not very sensitive to the

volumetric ratio of water to fuel in the core, the BWR neutron physics characteristics can be varied without deterioration in the heat transfer characteristics by changing the water-to-fuel volumetric ratio. Takeda et al propose to utilize this characteristic to attain a conversion ratio of 1.01 by MOX loading with a core of which the height is almost half of the current core height, without changing the steam quality at the exit or the temperature and pressure conditions of the reactor core[23]. Recycling of minor actinides in parallel with plutonium is also envisioned in this design. In order to realize this concept, however, development and/or confirmation testing are necessary in such areas as heat transfer characteristics in a short core made up of a tight lattice and reactor physics characteristics which should satisfy the requirement of negative void coefficient of reactivity.

To achieve this core of low water-to-fuel volume ratio, a combination of a hexagonal tight-lattice fuel bundle and a Y-shaped control rod is a preferred design option. However, it was found that halving the core height has a potential of achieving a high conversion ratio of 0.95, and even breeding, if a combination of a current square-lattice and a cruciform control rod design is used for core design with an appropriate blanket. Thus, achievement of higher conversion ratios with this strategy is part of the study on the next generation ABWR plant.

As for the PWR, a tight-lattice MOX-fueled high conversion-ratio PWR concept has been proposed for better utilization of uranium resources since the 1970's, e.g. ref. [24]. In recent years, however, a mixed-moderator PWR concept in which a certain amount of light water is replaced by heavy water to boost the conversion ratio has been proposed. This is viewed as a more realistic design for the next generation PWR in which the spectral-shift operation makes it possible to better utilize uranium resources while maintaining the technology of the conventional PWR [25].

2.2.3.3. Achieving Higher Thermal Efficiency

At the time of the LWR introduction into the power market, it was considered that pursuing scale merit rather than high thermal efficiency was a better solution for making the LWR competitive, although supercritical steam boiler technology was already developed, as the cost of nuclear fuel was relatively inexpensive at that time [26]. Nuclear power technology with high thermal efficiency has been demonstrated by the High Temperature Gas Cooled Reactor, for which high coolant temperature was pursued, as it was capital intensive due to its low power density. Currently JAERI is constructing the HTTR for exploring the feasibility of the HTGR for steam-reforming hydrogen production as well as power generation through a combined cycle [27].

However, the light water reactor has a potential for improving economics in this direction, although raising thermal efficiency through higher steam temperatures would not be realizable without painstaking efforts, especially for the development of fuel cladding. One such conceptual proposal is a supercritical light water reactor which sends steam at 434° C produced under supercritical pressure (25MPa) conditions to the turbine and achieves a thermal efficiency of 41.8% [28]. Since the coolant density in this reactor core is well below that of a conventional LWR, this reactor also has the potential of becoming a breeder.

2.2.3.4. Plutonium Incineration

Plutonium burning in LWRs via non-fertile matrices has been proposed as a means to incinerate plutonium from dismantled nuclear weapons. The matrix materials can be divided into two groups. One group includes such fluorite-type phases as ZrO_2 and CeO_2 which would be stable in acid solutions. The other includes such compounds as Al_2O_3, MgO, $MgAl_2O_4$ (spinel) which have higher thermal conductivity but lower chemical stability than the fluorite phase. Nitani et al proposed rock-like fuels in a $ZrO_2(Y, Gd)$-Al_2O_3-MgO system[29] and reported their preliminary results of the study on the phase stability of this fuel in a fluorite+spinel system using plutonium, simulated fission products and inert matrix materials[30].

2.2.4. Molten Salt Reactors

Molten Salt Reactor (MSR) concepts offer the potential to contribute to the world's energy supply in the time frame of interest in this paper. MSRs come in a great variety with many options [31]. Only MSRs with on-line fuel processing and external cooling are considered in this paper. External cooling means that the fuel itself serves also as the coolant and is circulated from the critical core to a heat exchanger which is external to the core. Only fluoride salts are considered as they are subject to the fluoride volatility process [32] which readily permits separation of the uranium from the salt. MSRs are unique in that they do not have a fuel cycle in the usual sense. Also, MSRs have extraordinary safety features [33] which derive primarily from their on-line processing and the fact that the fuel is a fluid. Fuel expansion upon heating pushes the fuel out of the core resulting in a strong negative reactivity temperature effect which provides control. The concept of a "meltdown" accident is meaningless for MSRs.

On-line continuous processing results in an equilibrium fuel that requires only a very little "excess" reactivity to compensate for control or "burn up" and hence there is no driving force for a reactivity excursion accident. Also, the radioactive source-term of MSRs can be made quite small via on-line fuel processing [37].

The "fuel cycle" of solid-fuel reactors is replaced in MSRs by a continuous equilibrium state. Criticality is maintained by continuous removal of fission products and the addition of fissile material for a converter or the removal of fissile material for a breeder. The only remaining portions of a "cycle" are the initial start up of a reactor with fresh fuel, and at the end-of-life of the reactor, the remaining fuel. However, even these insignificant residues of a fuel cycle are rendered meaningless if the reactor is started up with fuel from a previous reactor and the end-of-life fuel is transferred to the next reactor. Thus, there is no meaning to "burnup" in MSRs. A particular "batch" of fissile material can be burned completely (100% burnup) simply by leaving it in the reactor until it is consumed. This is significant when one type of fissile material, such as plutonium, is used. Plutonium can be burned completely and its last "residue" is replaced by another type of fissile material such as uranium. [35]

MSRs can be used to completely dispose of plutonium while utilizing the plutonium for energy generation. This property of total utilization of the fissile material, coupled with the high efficiency of MSRs, and the ability to thrive on Th-U fuel results in optimal long-term resource utilization with little environmental impact.

At the time MSRs were first studied, in the 1950s and 60s, the primary emphasis was on high breeding ratio and short doubling time. The terminology "fuel cycle" referred to the synergism of various reactor systems, rather than to the fuel management of a single reactor. The emphasis on breeding performance [36] is not expected to regain its past importance in the near future. There is now more room to develop and emphasize the non-proliferation and waste-simplification aspects of the MSR [37, 38]. The ability to dispose of Pu and HEU have already been mentioned. The utilization of Th-U-233 fuel also has non-proliferation advantages. The U-233 is protected by the high energy gamma radiation of the daughter products of U-232 which accompanies the U-233. The fluid nature of the fuel and its relatively high melting point require elaborate and sophisticated means for handling and manipulation which makes diversion and subsequent proliferation extremely difficult.

2.3. Other Concepts

There are many other thermal reactor concepts which could have been presented here, and the authors make no claim that these are the only, or even the best, options available in every circumstance

2.4. Summary and Conclusions

This paper has examined some of the potential for long term development of thermal reactors. There are many other concepts that may contribute to this potential. It is certain that development of a new reactor type, or even modification of an existing type, is a major undertaking. Nonetheless, as time progresses it may become essential to 'branch out' from familiar designs in order to maintain competitiveness with other energy supply options. The concepts outlined in this paper illustrate some of the alternative solutions which may find applications in general or specialized situations.

It is anticipated that thermal nuclear reactors will continue to play a significant role in the production of electrical energy and in other applications well beyond the year 2050. It is apparent from present schedules for introduction of fast reactors in the world that this reactor type will not become significant in the context of overall world energy supply until after 2050, and further that the preferred nuclear energy system may, for several decades, remain as a mixture comprised of a large population of thermal reactors and a relatively small but steadily growing population of fast reactors.

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FAST REACTORS: R&D TARGETS AND OUTLOOK FOR THEIR INTRODUCTION

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Abstract

In this paper the current status of fast reactors development is briefly outlined, including experimental, demonstration, and commercial installations. Data on the experience gained in development and operation of NPPs with reactors of this type are presented. The issues are discussed in connection with possibilities of fast reactor development in the nuclear power structure for the near (up to 2010-2020) and distant future. In the final part of the paper, an analysis is given of possible ways for R&D development in the field of NPPs with fast neutron reactors.

1. INTRODUCTION

Fast reactors (FR) have gone a complex way in their development. In different stages of nuclear power development, different requirements were imposed on reactors of this type from the standpoint of their characteristics. Answering the needs of practical power, designers of NPPs with fast neutron reactors demonstrated different (both positive and negative) FR characteristics. In this respect, one has to consider positions of specialists according to which FR are able to provide a safe and ecologically acceptable development of nuclear power. In spite of this reasonable position some opponents refuse any type of development of FR. With sufficient experience on the development, construction and operation of sodium cooled FR, it is possible to sufficiently characterize this reactor type and, on the basis of detailed analysis, to speak of the present FR role and to predict the possibility of their use in future.

2. CURRENT STATUS

The history of FR development totals approximately 45 years. The appearance of this direction in nuclear power was connected with a clear understanding of the fact that only in FR the most efficient utilization of natural uranium can be realized.

Worldwide, ten countries began to develop the FR technology at different times, including core physics, coolant technology, structure materials study, thermal hydraulics etc. The works were started in the early fifties from the creation of rather simple installations of the EBR-1 type in USA and the BR-1, BR-2 type in Russia. Later, works were started on the creation of experimental installations modelling major schemes of future NPPs, such as BR-5 in Russia (1958), DRF in the United Kingdom (1959), Rapsodie in France (1967), etc. A total of nine experimental installations were built in seven countries (Table I) [1].

The next FR development stage is the creation of demonstration NPPs. To date, six installations in five countries have been constructed in the power range of 60 through 330 MW(e). Three of them (BN-350, Phenix and Monju) are still in operation.

TABLE I. FAST REACTORS DEVELOPMENT IN DIFFERENT COUNTRIES

Country	EFR*		DFR**		CFR***	
	Built	Under design	Built	Under design	Built	Under design
China		CEFR				
Europe						EFR
France	Rapsodie		Phenix		Super Phenix-1	Super Phenix-2
Germany	KNK-II		SNR-300			SNR-2
India	FBTR			PFBR		
Italy		PEC				
Japan	Joyo		Monju			DFBR
Kazakh-stan			BN-350			
Russia	BR-10 BOR-60				BN-600	BN-800 BN-1600
UK	DFR		PFR			CDFR
USA	EBR-2 FFTF		Fermi	CRBRP ALMR		

* EFR - Experimental fast reactor
** DFR - Demonstration fast reactor
*** CFR Commercial fast reactor

The current status of FR technology corresponds to the operation of two commercial installations: BN-600 and Super-Phenix-1. Note that significant experience in commercial NPP development has been gained in France (Super-Phenix-1), United Kingdom (CDFR), and Germany (SNR-2), combining further their efforts in the development of a joint EFR project. Russia and Japan have also gained essential experience in connection with the development of the commercial designs BN-800, BN-1600 and DFBR, respectively.

3. EXPERIENCE IN DEVELOPMENT AND OPERATION

The total time of FR operation amounts to 280 reactor-years. On the basis of the experience gained in development, substantiation and operation of experimental, demonstration and commercial reactors the following can be noted:

(a) The breeding capability which was initially considered as an important feature of fast reactors has been fully established with Phenix and BN-350.

The question of the breeding capability deserves some remarks:

In the mid seventies, early deployment of breeders was considered to be urgent. There is no doubt that in the remote future this basic feature will recover its importance. But today, the concern is rather how to manage important stock piles of Pu and minor actinides.

(b) Now one can state that the major technical solutions in scheme design and safety systems have been determined and tested for NPPs with fast neutron reactors. A three circuit NPP lay out, sodium coolant and MOX-fuel can be assigned to these solutions. In practice, structure

solutions such as integral arrangement of a primary circuit, guard reactor vessel, SA structure with a rod type fuel pin, circulation pumps, IHX, etc. can be considered as commonly adopted solution.

An individual solution in each NPP project is made only for steam generators (SG). It can be explained by different approaches to solving safety issues for a given NPP component. The range of technical solutions for SG lies from integral (in one vessel) structure in the Super-Phenix-1 NPP to sectional-modular (24 modules) in the BN-600 NPP. However, both designs demonstrate reliable operation characteristics.

(c)   The problems of materials irradiation in connection with choosing structure materials, operating under FR conditions with high irradiation doses have been resolved (justification of the utilization of ferritic and austenitic steels in the range of maximum burn-out levels of 10-15% h.a.).

(d)   Practically, a high FR safety level has been proved, as determined by the joint effect of the following factors (Table II):

- peculiarities of physical reactor parameters;
- peculiar coolant features;
- unique engineering solutions.

Specific FR features provide their minimal effect on the environment and humans during NPP operation. Table III presents comparative data on heat and gas-aerosol radioactive releases for different NPP types as an example [2]. One can see from the table that heat

TABLE II. FAST REACTOR FEATURES PROVIDING ITS HIGH SAFETY

NPP elements	Features
Reactor (core)	- negative reactivity feedback in cases of power and temperature disturbances - stability of neutron pattern - no probability of local criticality formation - no poisoning effects
Coolant	- low pressure - low corrosion activity - high thermal capacity - considerable margin to the boiling point and high evaporation heat - capability of fission products retaining
Engineering approaches	- pool type of reactor - guard vessels on the equipment of radioactive primary circuit - passive elements of safety system - passive elements in decay heat removal system

TABLE III. HEAT AND RADIOACTIVE GAS AEROSOL RELEASES FOR DIFFERENT NPPS

Type of release	WWER-1000	RBMK-1000	BN-600
Heat releases GW/Gwe	2	2.15	1.35
Release of radioactive inert gases, Ci/Gwe.yr	$(1-3)10^4$	$(4-12)10^4$	$(0.6-4.1)10^2$

releases for a fast reactor are essentially lower as compared with thermal nuclear reactors. As for gas-aerosol releases, iodine-131, long-lived and short-lived nuclide releases are practically not available, and inert radioactive gas releases are mainly determined by experimental studies in "hot" chambers.

The issue of the safe use of sodium coolant is worthy of special consideration. It is a well-known fact that negative sodium parameters are connected with the chemical activity of sodium in relation to water and air.

The accidents occured in NPP SG with leakages of water into sodium have shown that the engineering methods for safety provision of sodium circuits are available in case of chemical interaction of the two coolants [3].

As for sodium leakages, with their subsequent burning, the probability of any severe fire can be lowered down to acceptable values thanks to adequate provisions. Sodium due to its small heat effect and fire rate cannot lead to substantial fires of the surrounding equipment. This was confirmed by sodium leakages occurred at operating NPPs [4,5]. Radioactive sodium leakages at integral equipment arrangement and availability of a guard vessel are of low probability. The low number of sodium leakages at reactors with a loop equipment arrangement has shown that fire-fighting systems are capable of fully localizing the radioactive fire products.

(e)   From the point of view of engineering parameters, rather high temperatures at the core outlet and temperature and pressure of steam have been mastered in fast reactors (Table IY). The parameters indicated provide good parameters of thermal dynamics for the steam-water cycle (gross efficiency is up to 42%).

Basically, the efficiency of fast reactor operation is also determined by the fuel burn-out level. For power installations a maximum fuel burn-out in standard SA reaches 12-15% and exceeds 30% for experimental installations (BOR-60, Russia).

(f)   What is the experience gained from the viewpoint of the economical efficiency of fast reactors?

The experience gained on fast reactors has shown that investments are more important than for light water reactors. In the case of a prototype the investment may reach 1.5 times the investment of a light water reactor. In the case of a series production, French studies in the frame of EFR indicate that the investment does not exceed 1.2 times the investment of a light water reactor. These differences are explained by the following reasons:

•   For sodium cooled FR an "extremely pure" technology is necessary;

TABLE IV.   MAIN CHARACTERISTICS OF FAST REACTORS ON THE CURRENT STAGE OF THEIR DEVELOPMENT

Parameters	Value
Sodium temperature at the core outlet	up to 565^0C
Superheated steam temperature	up to 510^0C
Superheated steam pressure	up to 18 Mpa
Efficiency (gross)	up to 42%
Maximum fuel burn-up in standard S/As	up to 15% h.a.
in experimental S/As	up to 32% h.a.
Average specific metal consumption	not more than 13t/MWe

- The use of uranium-plutonium fuel in a fast reactor requires some expenditures for regeneration of NPP spent fuel;

- All constructed NPPs with fast neutron reactors were unique representatives which, on the one hand, essentially impairs the economical parameters of these installations, and, on the other hand, did not allow to objectively determine FR reactor competitiveness as compared with commercial units of other NPP types.

4.   PROJECTS FOR DEVELOPMENT

Stores of accumulated, economically efficient uranium in the world will be sufficient up to 2030-2050 for any scenario of nuclear power development [6]. In this connection one can show that in the near future the positive FR features will not be needed.

This relates primarily to FR capability to reproduce nuclear fuel. At the same time, the use of fast reactors for electrical power should not be expected in near future, because a well mastered light water reactor technology is available and besides fast reactors (as mentioned above) are still exceeded by light water reactors in economical characteristics.

The FR construction during the next decades will be justified if used rationally as NPPs with modern safety characteristics and for the solution of ecological problems connected with spent nuclear fuel and efficient use of plutonium stores (both civil and weapon-grade).

In this case it is necessary that the generation which uses "nuclear electricity" should resolve the problems of long-term handling of nuclear fuel cycle wastes rather than convey these concerns to the next generations.

The ways to convert a fast reactor from breeder to actinide burner are well studied at a conceptual level and consist in the replacement of breeding blankets by non-breeding and the modernization of the traditional core, for example, by increasing fuel enrichment or using fuel without uranium-238.

If we consider the problem of efficient plutonium utilization (both civil and weapon-grade) in a fast reactor as a special task of actinide utilization, the following should be noted [7]:

- Although studies are still in progress it already appears that the conversion of a reactor-breeder to a reactor-burner does not lead to any serious problems connected with the reactor physics and with its safety provision and that fast reactors may have an essential role to play due to their ability to recycle Pu, because they can accomodate a high amount of pair isotopes and, at the same time, burn higher actinides (without producing a prohibitive rate of minor actinides thanks to their low level of capture).

- Weapon-grade plutonium utilization in a fast reactor permits "to control" in a wide range the level of its denaturation and, consequently, to solve in an optimum way problems connected both with subsequent civil use of plutonium and prevention of its use for military purposes. In any case, the denaturated plutonium should be reliably "brought out" of the weapon-grade plutonium standard;

- Plutonium utilization in a fast reactor is highly efficient from the safety and ecology standpoints. In this case the term "efficiency" means the provision of reactor safe operation and non-proliferation of plutonium, which will be in inverse proportion to the number of reactor years per unit of plutonium used, and also the provision of safe handling of spent

fuel, which will be in inverse proportion to its total mass and MOX-fuel content in it per unit of plutonium used.

To illustrate the above statements, comparative data are presented in Table Y on the parameters listed above when using the reactor-burner on the basis of BN-800 (breeding blankets are absent BR<1), and WWER-1000 type reactors modernized for MOX-fuel (1/3 loading).

From the standpoint of a more general ecological problem connected with the utilization not only of plutonium but also of minor actinides (Np,Am,Cm), it is appropriate to consider a system consisting of thermal and fast reactors, which is capable "to close" all actinides created in it [8].

As an example, a system is considered below which consists of a fast reactor of the BN-800 type with fuel enriched to 37% by plutonium and a thermal reactor of the WWER-1000 type with uranium fuel. Plutonium and MA are separated from reactor spent fuel and pass to a fast reactor fuel where actinides are in a recirculation regime. The calculations show that in this system a slow increase of actinide is observed in fuel for fast reactor loading (equilibrium composition establishes after 17 cycles with content of Np, Am, Cm up to 10-13% of the plutonium quantity). In this case one reactor of the BN-800 type with 10% burn-out is capable "to serve" 1.5 reactors of the WWER-1000 type.

To enhance the ecological safety of the system it is appropriate to locate a MOX-fuel production plant, a radiochemical plant and a fast reactor at one closed territory. In this case only WWER spent fuel will arrive at the site. For example, under Russian conditions, the optimal region for construction of the complex of installations mentioned, as a component of a thermal and fast reactor system in the initial stage is the South Ural region (integrated plant "Majak").

We can believe that a real state of the art FR and a chosen nuclear fuel cycle strategy will determine their development in different countries in near future.

If we choose a strategy of deep geological burial of spent fuel without its reprocessing, this can lead to some delay in FR construction. A similar approach is presently pursued in the USA [9], although the GE developments on ALMR installations are of interest both from the standpoint of reactor design and fuel cycle technology.

The strategy of spent fuel reprocessing with the use of uranium restored in PWR reactors and plutonium in light water and fast reactors is unique in France and Japan. This way is possible when MA and high active fission fragments are removed to a storage or MA are separated and burned in a fast reactor.

In the countries mentioned, a particular place in nuclear power is provided for FR, and the start up of Monju NPP in Japan and the operation of Phenix and Super Phenix in France confirm this. One can suppose that in the near future FR in France and Japan will not lose their position. Some peculiarities in FR development exist in Russia:

- Spent fuel reprocessing is carried out with the separation of uranium and power plutonium (fuel from WWER-440, transport and fast reactors), and excess weapon-grade plutonium is released. For Russia, a partial replacement of uranium by plutonium as fuel for NPP is useful in connection with the possibility to sell uranium at the external market [10];

- Technological readiness of FR in Russia for plutonium utilization is higher than light-water reactors (operation of cores with plutonium at BR-10 and BOR-60, SA testing with MOX-fuel at BN-600);

132

• Economical parameters of NPP with FR (BN-800) under development are approaching those for new light-water reactor projects (NP-500, WWER-1000);

• An essential positive experience has been gained in Russia in development, construction and operation (110 reactor-years) of FR having different power.

Taking into account the above and in accordance with the nuclear power development concept up to 2010, the construction of 3 - 4 BN-800 units with uranium-plutonium fuel is planned. The solution of electrical power tasks is considered jointly with the complex of ecological problems, including utilization of civil and weapon-grade plutonium.

Certain progress in FR development is observed also in other countries [11]. The main goal is to create the nuclear power which would lead to a of self-provision regime for nuclear fuel.

The works in India continue on a prototype fast reactor of 500 MW(e) (Indira Gandhi Centre for Atomic Research). In the Republic of Korea, work is in progress on a prototype FR 150-350 MW(e) with a planned start-up not later than 2011. The first commercial reactor is planned to be built in 2025.

Intensive works are carried out in China on the CEFR-25 experimental reactor project, wich is planned to start-up just after 2000.

5.   DIRECTIONS OF FUTURE R&D WORKS

As regards the "large scale" nuclear power in the future, which could take one of the leading positions in the world's power generating complex, there are grounds for attaching great importance to the role of fast reactors. This is because of their high safety level, good environmental characteristics, and capability of nuclear fuel breeding.

However, while the scientific and technological tasks related to the reactor safety assurance and breeding characteristics have already been solved, additional studies are still required to find optimum technical approaches when designing reactors for the efficient utilization of actinides and, in particular, improving their technical and economical characteristics.

At the same time, these are the key tasks to be solved for enabling the use of fast reactors within the period of 2030-2050, when their function as nuclear fuel breeders will not be required yet.

(a)   The increase of economical competitiveness of fast reactors is connected with various R&D directions. First, further improvement of the NPP lay-out, main component design and parameters are required. Studies have shown that there is a significant potential for decreasing the amount of materials in the equipment, simplification of the electric circuits, etc. Positive experience has been gained in this field in Russia and in France. For instance, taking into account the experience of the BN-350 and BN-600 reactors operation in the BN-800 reactor design has resulted in the decrease of the amoung of material in the equipment (Table 4). Besides, design studies of the BN-600M medium size advanced reactor, based on the new lay-out and design approaches (such as integral steam generator design) have demonstrated the possibility of further improvement of fast reactor economics.

Similar results have been obtained when designing the 1500 MWe EFR fast reactor [11, 12]. Possible economical characteristics forecast for commercial EFR reactors as compared to those of the advanced PWR show that the capital cost ratio may be within the range of 1.1÷1.26 depending on the specific site conditions (Table 7).

TABLE V.   COMPARATIVE CHARACTERISTICS OF VARIOUS SCENARIOS OF
            PLUTONIUM UTILIZATION IN REACTORS

Parameters	BN-800	WWER-1000
Number of reactor-years per 1 ton of utilized ex-weapons plutonium	0.58	3.73
Amount of spent fuel per 1 ton of utilized ex-weapons plutonium	5.9	83.6
Amount of spent MOX fuel per 1 ton of utilized ex-weapons plutonium	5.9	27.8

TABLE VI.   SPECIFIC STRUCTURAL STEEL CONSUMPTION VALUES FOR LMFR
             AND WWER (IN TON/MWTH)

BN-600	BN-800	BN-600M	VPBER-600	WWER-1000
13	10.5	8.23	9.7	8.44

TABLE VII.   ECONOMICAL CHARACTERISTICS OF ADVANCED REACTORS
              (EFR AND PWR)

Characteristics	EFR	PWR
Components of electricity cost, fc/kW-hr		
capital cost	13.5	10.7
operating cost	4.4	3.9
fuel cost	4	5.1
electricity cost	21.9	19.7
EFR/PWR characteristic ratio		
capital cost	1.26	
electricity cost	1.11	

Second, it should be also taken into account that the current rate of power engineering increase (including that of nuclear power) is significantly lower than it was predicted 20 or 30 years ago. Besides, a considerable amount of plutonium has been accumulated. Under these conditions, there is no need in the short doubling time value for the near term fast reactors, i.e. the uranium blanket can be eliminated, the core power rating can be reduced, and the fuel cycle can be simplified. All these measures not only improve the reactor safety, but also favour further improvement of its economical characteristics.

Third, the decrease of the fuel related component of the cost of electricity generated by the fast reactor NPP is quite essential. From this point of view, R&D works aimed at the increase of the fuel burnup to 15% or 20% and relevant development of the new S/A and fuel element designs and materials having improved performance under the high fluences become urgent.

Fourth, some factors influencing economical characteristics of fast reactors have not been taken into account. As it has been mentioned above, fast reactors are capable of having high reliability, safety and efficient environmental characteristics. However, methods of technical and economical analysis have not yet been developed for taking into account these positive

features of fast reactors (high availability, low radioactive releases, decrease of the total radiotoxicity of spent fuel, etc.). For instance, it is easy to take into account economical losses caused by the introduction of the intermediate sodium circuit, while it is difficult to estimate (there are no appropriate methods) the benefits caused by taking out the steam generator failures from the category of radioactive accidents.

(b) A considerable amount of R&D works carried out recently, and those planned for the future are devoted to the development of special core designs of reactors for burning minor actinides and efficiently utilizing plutonium.

In order to carry out these studies, the CAPRA programme (France) is currently under way, which is principally aimed at the development of scientific and engineering approaches for plutonium utilization. The SPIN programme (France) is devoted to the solution of tasks related to the minor actinides transmutation in fast reactors.

The PAC programme (France) developing the idea of using the Super-Phenix reactor for the experimental studies, is an example of the efficient application of reactor plants under operation for the purposes of plutonium utilization.

Studies related to the development of fast reactor design intended for plutonium utilization have also been made recently in Russia. R&D works are carried out in conformity with the BN-800 reactor design being aimed at the development of various core designs for this reactor. Core concepts have been developed on the basis of both MOX fuel with increased content of plutonium, and the inert matrix (AlN, MgO, ZrC) based uranium-238 free fuel. Some studies are conducted using ISTC funding.

(c) Further improvement of fast reactor safety is still an urgent issue, taking into account technical and economical optimization of the safety systems. In this respect, special attention should be paid to the systems operating on passive principles (devices for the reactivity control, decay heat removal systems, etc.).

When developing the new methods of accident analysis, much attention should be given to the creation of calculational multi-dimensional systems taking into account neutronics, thermohydraulics, thermomechanics and radiological phenomena. Such works have been initiated in France, Japan and Russia. The SERAPH code (Japan) is an example of a tool for the comprehensive study of phenomena taking place in fast reactors.

(d) R&D works in the field of technological studies should first of all relate to the issues of improvement of fuel cycle technologies. Special attention is given to the development of various technologies of reprocessing of spent nuclear fuel having a high burnup. In Japan, for instance, the RETF facility is under development which is intended for testing equipment for recycling of the spent fuel. The AFRS programme (Japan) is developed for comprehensive studies on the fast reactor fuel technology, which are supposed to be widely used in the first decades of 21st century.

The issues of further improvement of safety related to the sodium technology are still urgent (improvement of the sodium leak detection methods in order to prevent large leaks, improvement of methods of the sodium fire confinement, etc.). Such studies are actively carried out in France, Japan and Russia.

The search has been initiated for the new coolant alternatives (such as lead and lead-bismuth alloy), which are possibly capable of improving NPP safety.

In connection with the trend to increase the NPP design life-time, the development of new methods of equipment inspections and residual life- time estimation are required.

It is necessary to extend R&D works on NPP decommissioning, while the experience gained by now in the process of the dismantlement of research reactors (in France, UK and Russia) is to be used for making recommendations for the future designs in order to significantly decrease their decommissioning costs. In Russia (IPPE), for instance, a concept of fast reactor decommissioning has been developed on the basis of an optimum design of the reactor shielding, the introduction of new materials (titanium and nickel free steels), which almost do not produce long living activity, the creation of a closed cycle of radioactive materials in the framework of the nuclear industry, etc. [14].

6.   CONCLUSIONS

(a)   Fast reactors which have passed experimental, demonstration and commercial stages during 45 years, demonstrate satisfactory performance from the standpoint of reliability and safety, thus confirming their maturity with respect to the main approaches in technology. The key feature of fast reactors - nuclear fuel breeding - has been experimentally substantiated.

(b)   Taking into account the low rate of development of power engineering as a whole and in particular of nuclear power, as well as the considerable uranium resources, the most important feature of fast reactors, namely their capability to breed nuclear fuel (i.e. extensive introduction of fast reactors into the nuclear power) may be required not earlier than in 2030 - 2050.

(c)   There are ways for the significant improvement of fast reactor economics and their safety. Ways of using these reactors for the efficient burning of the radioactive wastes of spent fuel and plutonium utilization for electricity production are substantiated.

(d)   Taking into account the above considerations, single commercial NPPs with fast reactors can be built in the countries possessing sophisticated technology of these reactors (France, Russia, Japan, etc.) until 2030. There is still an interest for the construction of experimental and demonstration reactors in those countries, where the studies on the technology of fast reactors have been initiated (China and Korea).

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136

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FUEL CYCLE TECHNOLOGIES - THE NEXT 50 YEARS [1]

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Abstract

World energy demands are set to increase through the next Millennium. As fossil fuel reserves fall and environmental concerns increase there is likely to be a growing dependence on nuclear and renewable sources for electricity generation. This paper considers some of the desirable attributes of the nuclear fuel cycle in the year 2050 and emphasises the importance of considering the whole of the fuel cycle in an integrated way - the concept of the 'holistic' fuel cycle. We then consider how some sectors of the fuel cycle will develop, through a number of multi-national contributions covering: enrichment, fuel, aqueous reprocessing, non-aqueous reprocessing, P&T, MOX, direct disposal, waste. Finally, we summarise some of the key technical and institutional challenges that lie ahead if nuclear power is going to play its part in ensuring that planet Earth is a safe and hospitable place to live.

1. INTRODUCTION

All credible predictions suggest that World energy demand will grow through the next Millennium. Such demand needs to be balanced against environmental constraints and the availability of raw materials; meeting the World's energy needs in this sustainable manner is a huge challenge to mankind.

Many reviews of World energy demand have been published [1]. Electricity generation makes a significant impact [2], not just because power generation has a great influence on the environment, but also because increasing industrialisation and quality of life in the developing nations leads to much increased electricity demand. Almost 17% of total demand is produced by nuclear power stations today. In view of the reducing reserves and environmental effects of fossil fuels, it is expected that there will be increasing reliance upon nuclear and renewable generation. It is projected that maintaining nuclear at 15% of the World electricity generation would require some 1000 GWe of capacity by 2050 (compared to 350 GWe today); achieving the World Energy Council projections for energy mix suggest the need for about 2500 GWe on the same timescale [2].

It therefore seems inevitable that fuel cycle services will also be required in 2050. The nature of these services will change as the reactor mix changes and as differing technologies mature and fade in response to customer demand, regulatory challenge, public perception and political pressure. The fuel cycle facilities of tomorrow are driven by the need to achieve:

- demonstrably high levels of safety;
- minimum overall fuel cycle costs;
- minimum overall environmental impact, including minimum waste generation;
- maximum utilisation of natural resources;
- minimum proliferation risk and maximum safeguards visibility;
- public support;
- diversity and security of energy supply.

These requirements, which are not necessarily in any priority order, are comprehensively discussed elsewhere [3]. However, it is appropriate to re-emphasise one particular concept - the 'holistic' fuel cycle.

The 'holistic' fuel cycle considers the complete fuel cycle as a whole, rather than as a number of individual stages. Figure 1 illustrates how the concept integrates the various options for fuel manufacture, reactors, reprocessing, waste management and decommissioning to optimise the whole fuel cycle within the requirements of the total nuclear system [4]. Minimising total cost, maximising safety whilst reducing waste generation are all key factors and are consistent with the requirements listed above. The holistic fuel cycle is a long-term, maybe idealistic target - but it is a target worth striving for. To achieve it will require more flexible processes, greater synergies between existing systems and those planned for the future, more emphasis on co-ordination between the sectors and a greater role for international collaboration.
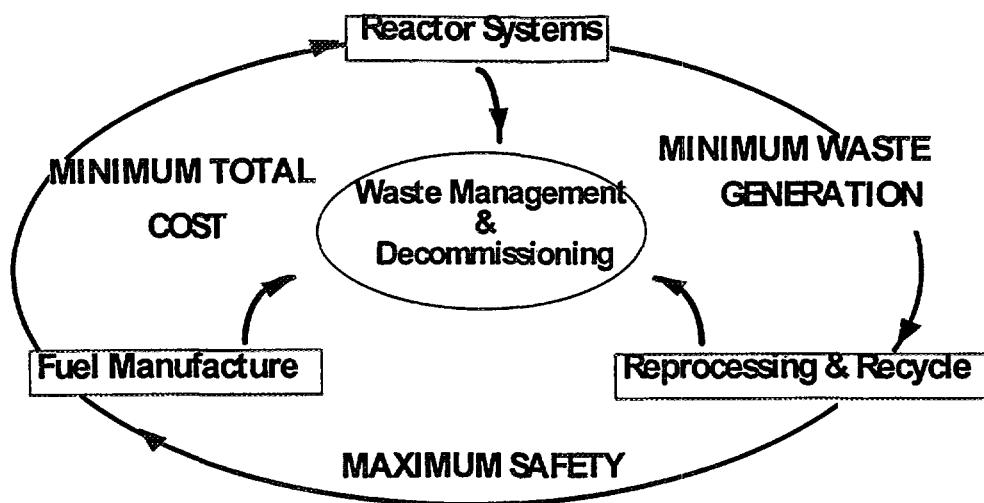
FIG. 1. The Holistic Fuel Cycle [4]

The purpose of this paper is to provide an international perspective on some of the emerging fuel cycle technologies that may be expected to see commercial realisation in the period 2015-2050.

2. FUEL CYCLE TECHNOLOGIES TO 2050

2.1. Centrifuge enrichment

J. Paleit, Urenco, UK

There are currently four primary enrichment suppliers in the long-term enrichment market - the United States Enrichment Corporate (USEC) which operates two plants utilising the gas diffusion process in the USA, Cogema/Eurodif which operates one diffusion plant in France, Urenco which

operates plants utilising the gas centrifuge process in Germany, the Netherlands and the UK, and Tenex which operates four gas centrifuge plants in Russia. Small enrichment plants are also operating in China and Japan. The total capacity of these plants is some 55 million separative work units (SWU) per year or sufficient to cover the annual enrichment requirements of over 500 reactors of 1000 MWe capacity. This may be compared to an annual demand for enrichment services of around 38 millionSWU/a over the next ten years.

The enrichment services provided by the gas diffusion plant operators cover some two thirds of demand today with the plants at 70% of their nominal capacity. This level is close to their commercial maximum at today's market prices since above this level power costs for the diffusion plants rise considerably. A diffusion plant requires some 2300-2500 kWh/SWU.

By 2015 the diffusion plants in the USA will have reached the end of their lifetime following 55 years in operation. Even today they struggle to meet current licence standards and maintenance costs are high. In France the diffusion plant will be approaching 35 years in 2015 and be facing replacement.

The most modern enrichment technology today is the gas centrifuge, particularly that developed in Europe by Urenco. A number of design generations have been introduced over almost 25 years with modular installation of units having continuously improving efficiency and competitiveness. Costs are closely controlled and there is further technical potential already being developed.

The Tenex gas centrifuge plants are of an early design similar to that introduced by Urenco in the early 1970's. It is questionable whether this capacity can be maintained in operation in 5, 10 or 15 years time. Further the economics becomes more difficult as market economy principles are introduced. New centrifuge technology will require considerable R&D investment.

Looking ahead the first technology question will be what process will replace the gaseous diffusion plants by about 2015? Currently laser separation is being pursued as a possibility at laboratory scale (AVLIS or SILVA in the US and France respectively, MLIS in South Africa also with French investment). In Australia USEC is an investor in the SILEX process. A number of other routes, eg jet nozzle, helikon process and crisla, have been pursued in the past but not commercially proven on an industrial scale.

Experience has shown that new technology is fraught with development complexities, technical uncertainties and high cost. It will be for governments as well as the enrichment industry itself to determine how much capital is invested in new technology. This will also depend on the future growth of the nuclear power industry worldwide. One alternative to new technology is further exploitation of the gas centrifuge. This also has the advantage in its ability to re-enrich reprocessed uranium which is already offered as a routine service.

Looking beyond the period 2015-2020 towards 2050 is inevitably more speculative but the above comments also apply. In summary it is likely that technological development in the enrichment industry will be evolutionary rather than revolutionary in the next 50 years.

2.2. Laser enrichment

A. Schillmoller, GE, US

The traditional enrichment of virgin uranium through the centrifuge and diffusion processes has historically provided as much as 95% of the Western World's enriched uranium supply with non-traditional sources providing the balance. However, it is now clearly apparent that the ageing diffusion plants are approaching technological and economic obsolescence. These plants and

technology must surely be replaced by 2025. The United States, France, and Japan have announced programs that may lead to the deployment of laser enrichment technologies. The most advanced of these programs, AVLIS and SILVA, enrich uranium in the form of a metal alloy, in contrast to the Russian and Urenco advanced centrifuge programs which handle gaseous uranium hexafluoride. The deployment of laser enrichment has major implications for both the uranium conversion and fuel fabrication segments of the industry where the potential receipt of uranium in both a metal and UF_6 form may lead to significant restructuring.

USEC has announced the scheduled operation of the first AVLIS laser enrichment facility for 2005. Cogema has not yet announced a deployment date for SILVA or MLIS, but by 2025 the Pierrelatte facilities will be approaching 50 years old and due for replacement. Since AVLIS and SILVA process uranium in the form of a metal alloy, UF_6 may no longer be traded universally for either natural feed or enriched uranium product. This may necessitate both a new front end product for laser enrichment and also a new back end product for delivery to the fuel fabricators. The enricher faces the choice of delivery of uranium to the fabricator in the form of metal, UF_6, or oxide. It is anticipated that some form of extraction process will be required to remove all contaminants from the uranium alloy. This may be done at either the enrichment facility, at a central reconversion plant, or at the individual fabricators. The enrichment enterprise also faces the decision of reconversion technology, plant(s) size and location. Economics, safety, and environmental considerations will enter into the decision. A probable outcome is that existing solvent extraction (Purex) technology will be used to process the uranium alloy and that the resultant uranyl nitrate will be converted to uranium oxide at central reconversion plant(s).

Therefore by 2015, the fuel fabricator may be facing a new reality. Enriched uranium product may be available in the form of UF_6, uranium alloy, and oxide. The fabricator will face the decision of maintaining duplicate facilities and technologies to deal with the various uranium forms or working with others to rationalise the diverse forms of uranium feed. The maintenance of duplicate capabilities and facilities by the individual fabricator will entail the worst of both worlds. To avoid this problem, we believe that it is logical that central reconversion facilities will be constructed by the enrichers and that the fabricators will consolidate UF_6 processing capacity by shutting down the older wet ADU processes.

The fabricator will consider four broad criteria in determining the acceptability of uranium for processing: (1) ALARA, (2) Quality, (3) Fuel Performance, and (4) Cost. Laser enrichment provides a safe, environmentally sound and acceptable industrial process for transporting and manufacturing enriched uranium dioxide. Current technology involves the shipment and processing of UF_6 gas into UO_2 powder and pellets. The atomic vapour laser process will ship and process a uranium metal alloy in the form of ingots. The environmental and industrial safety problems of shipping and handling UF_6 gas cylinders are eliminated and leakage to the environment will no longer be a concern. The difficulty and hazards of processing fluoride gases, hydrofluoric acid and solid fluoride wastes are also avoided.

Compared to gaseous diffusion and gas centrifuge technology, the laser enrichment process is safer, reduces total energy cost and protects the environment.

2.3. Fuel

K. Hesketh, BNFL, UK

The long-term evolution of fuel product and manufacturing technologies will largely be dictated by the mix of reactors that will exist. The nature of this reactor mix has been, and will continue to be debated in detail elsewhere. One vision of a nuclear industry revived by growing global electricity demand whilst fossil fuel reserves fall and global warming is kept in check is:

142

- Existing LWRs will be shutdown, or at least be middle-aged by 2015. New-build will be APWR or ABWR, with further enhanced designs being considered after 2020.

- Helium-cooled graphite moderated high temperature reactors are commercialised having advantages of high thermal efficiency, intrinsic safety of high melting point fuel, single phase coolant and no need for metallic cladding.

- Fast breeder reactors also become available, driven by increasing uranium prices, flexibility to keep plutonium stocks in balance and recognition that they generate far fewer minor actinides per GWye.

- Reprocessing will be accepted, but must compete economically with interim storage. Plutonium becomes a scarce resource.

So existing and advanced LWRs will be operating in 2015, whilst further advanced thermal reactors, high temperature reactors and fast breeder reactors will co-exist by 2050.

Against this possible background, let us consider now some of the issues relating to fuel.

The economics of thermal reactor fuel will depend upon both the 'front end' and the 'back end'. In the 'front end', the economics improve with burn-up to about 55-60GWd/t. Beyond this level, the separative work function rises steeply and the corresponding irradiation times imply a greater discounting penalty, both of which restrict the likely economic burn-up. In the 'back-end', both reprocessing and direct disposal costs are likely to increase with burn-up. When all these effects are taken into account, the economic optimum burn-up of thermal reactor fuels are not much different from today's technological capabilities - up to about 60GWd/t.

As to the future technical limitations on fuel burn-up, it is considered that for a reprocessing cycle, the likely range will again be about 55-60GWd/t. Extending burn-ups beyond this range may not be optimal because of increased difficulty and expense of reprocessing more active fuels, decreasing fissile quality of plutonium (particularly if considered for re-use in thermal reactors) and low U-235 assay. Therefore, minor developments in fuel design and cladding are all that will be required.

For the once-through cycle, much increased 'back-end' costs may drive burn-ups towards 80 or even 100GWd/t. However, current cladding has little prospect of achieving such levels of burn-up and a radical alternative - such as ceramic cladding will be required. Furthermore, the much higher power peaking factors associated with high burn-ups will take the fuel too close to its fundamental limits, such as melting point. A new fuel design will therefore be required.

High temperature reactor fuel will use coated particles - uranium dioxide or MOX inside a silica or silicon carbide shell, possibly pressed into blocks incorporating graphite or maybe as a pebble bed. Fission gas retention should be good and there is no requirement for cladding, hence there should be few barriers to achieving very high burn-ups and setting the economic standards against which the LWRs will have to compete.

There are several other fuel cycle options that are likely to be relevant in the period 2015-2050:

- Use of recycled uranium. Current enrichment processes enrich U-236 (a neutron absorber) and U-232 (with strong gamma emissions from its daughter products making fuel fabrication difficult) as well as U-235. Selective enrichment of U-235, for example by laser isotope enrichment, would allow use of recycled uranium of lower assay. However, fuel from recycled uranium can only remain a small proportion of world's fuel

supply, though it might be a useful strategic resource if uranium prices increase dramatically.

- New reprocessing technologies may chose not to separate U and Pu to present levels of purity with consequential effects on fuel manufacture. Examples may be pyroprocessing followed by vibro-manufacture (Section 2.5) or concentrating Pu to about 20% in uranium and finishing to fuel by a gel route.

- Thorium-based fuel cycles may form a minor part of the overall nuclear capacity, though current views are that the theoretical advantages are insufficient to achieve dominance over uranium/MOX cycles and that the claimed non-proliferation benefits may not gain full public acceptance.

- MOX recycle in LWRs will be accepted, partly through disposition programmes, though its use will be relatively small scale. Reprocessing and reuse in LWRs, or high temperature reactors, prior to optimising its value in fast reactors is likely. Ultimately MOX will need to be disposed of, whether or not it is recycled further.

It is therefore concluded that advances in fuel technologies over the next 50 years will be driven by the prevailing reactor mix, by economics and by the need to integrate fuel manufacturing with adjacent segments of the fuel cycle, for example, the output from reprocessing plants.

2.4. Aqueous reprocessing

N. Camarcat, CEA, France
P. Pradel, COGEMA, France

The World's current reprocessing technology is the 50-year old PUREX process, with associated waste treatment operations. The conservatively-designed PUREX process achieves a high recovery efficiency and meets defined end-product specifications. Incremental improvements, for example in the performance of the extraction cycles, will lead to lower activity levels in effluents and improved operating practices will lead to reduced waste volumes.

However, in addition to technologies targeted at cost reduction and enhanced safety, a future objective is to reduce the total potential radiotoxicity of the waste to be disposed of. This can be achieved by reducing waste volumes and, particularly in the longer term, by reducing the toxicity of the wastes for disposal through further separation and treatment of their actinide content. The SPIN (SeParation-INcineration) programme in France is a good example of a national programme aimed at such a flexible and complete scheme for HLW management. The SPIN programme involves two sub-programmes:

PURETEX, for the short and medium term, endeavours to reduce the volume and activity of reprocessing waste from $1.5m^3$ to $0.5m^3$/tHM (against 1.7 m^3/tHM for direct disposal in the once-through cycle). The optimisation involves volume reduction, decreased activity in wastes and discharges, and improved matrix confinement properties.

For liquid waste, preference is given to evaporation processes over precipitation processes and the activity of discharges to the environment is reduced by sorting the effluents at source. CEA is also developing incineration or the mineralisation of organic compounds. For solid waste, the search for techniques best suited to each type of waste such as incineration of burnable waste, compaction of compressible waste, fusion of metallic waste and mineralisation of oxidisable waste are under investigation.

144

A large part of the PURETEX programme is connected with industrial projects of COGEMA:

- A new waste management scheme for low and medium active effluents at La Hague, has led to the elimination of coprecipitation and the associated bitumen wastes;

- The replacement of waste grouting for hulls and end fittings by a more efficient process of compaction;

- The construction of a facility for processing by-products and alpha wastes.

ACTINEX, for the long-term, is oriented towards the reduction of the ultimate waste quantity and toxicity. ACTINEX will assess the various separation and transmutation strategies, their advantages, their feasibility, and their use in novel nuclear schemes (including recycling of minor actinides in fission reactors and hybrid systems).

It is first necessary to assess the way to reduce the potential radiotoxicity of the spent fuel containing uranium, plutonium, fission products and minor actinides where the main contributors to the radiotoxicity include americium, curium and neptunium isotopes (since plutonium has been separated by classical PUREX process). Separation of americium and curium is difficult. Specific processes such as the DIAMEX or the SESAME process using innovative schemes of solvent extraction with new organic molecules are under development. Fundamental research also goes on for selected fission-product separation, especially for technetium, zirconium and caesium.

Aqueous reprocessing technologies are continuously under development and can be adapted to a large range of environmental choices. For the mid- and long-term, advanced fuel cycles will represent opportunities to take technology towards a more flexible and complete scheme for HLW management. R&D programmes are in progress to assure this objective and to confer benefits in fissile material utilisation and in environmental concerns over current conservatively-designed cycles.

2.5. Non-aqueous reprocessing

V.B. Ivanov, RIAR, Russian Federation

Non-aqueous methods are possible new technologies for the fuel cycle. Indeed fuel reprocessing plants constructed after 2015 may be based on such flowsheets. The non-aqueous processes tend to be shorter and simpler (fewer operations) as well as ensuring the containment of hazardous components within the system and the ready compatibility between reprocessing and fuel manufacture. They also tend to demonstrate the desirable attributes listed in Section 1 (above).

Several examples of the development and application of non-aqueous processes already exist. Here we will consider the molten salt, fluoride volatility and DUPIC technologies.

Pyroelectrochemical reprocessing using molten salts includes the following main stages:

- dissolution of the irradiated fuel in molten salts (mainly molten alkali chlorides at 450-700°C);

- decontaminating the fuel by electrolysis or other methods;

- minimal treatment of the products (such as removal of salts and crushing, melting or liquid metal vacuum extraction) prior to remanufacture of the fuel.

This approach has been applied to oxide fuel (RIAR, Russia), metal fuel (Argonne National Laboratory, US) and nitride fuel (JAERI, Japan) with suitable modifications. Benefits include:

- high chemical stability
- high dissolution capacity (more than 30 wt %)
- no neutron moderator
- improved proliferation resistance
- generally performed in one compact device, leading to lower production costs
- minimised HLW volume through concentration of fission products from the molten salts
- final products are ready for fuel manufacture
- suitable for wide range of fuel types without the need to alter equipment

Though the technology was developed for FBR fuel (eg for oxide fuel at RIAR or metal fuel at Argonne) there is sufficient experimental data to demonstrate the applicability for LWR fuel. Indeed, these processes have been tested on a semi-industrial level and are ready for commercialisation.

A second non-aqueous technology is fluoride volatility. This well-known process has some safety drawbacks as a large portion of the radioactive materials is transferred into the gaseous phase. However, techniques are available which can allow only the uranium to be extracted (as UF_6) from the irradiated fuel, keeping all other products solid. If necessary, a pyrochemical treatment can extract the plutonium dioxide from the fluorination residues (the CENTAUR process). This process is particularly suitable for reprocessing long-cooled fuel in order to extract good quality uranium suitable for further enrichment.

In future, there may be limited application of methods for direct repeated irradiation of fuel. The DUPIC (Direct Use of PWR fuel in CANDU) programme in South Korea is an example. Though this method has yet to be demonstrated on a large scale, feasibility studies are encouraging. Similar principles can be used for internal recycle of FBR fuel especially for fuel containing minor actinides for transmutation.

All these technologies have been experimentally proven to differing degrees. They can be modified depending on the reactor types used in future and will permit the reduction in recycle duration by integrating reprocessing and fuel manufacture.

2.6. MOX

M. Katsuragawa, PNC, Japan

Plutonium utilisation in existing LWRs as MOX fuel has now reached commercial maturity in France, Germany, Switzerland and Belgium. Japanese utilities will also start to use MOX by next century. It is estimated in the year 2005, about 400t of LWR MOX fuel will be loaded annually in these countries. This trend will be continued and progressively accelerated by increasing the number of licensable LWR plants and the loading level of MOX fuel from the present partial core to full cores. Furthermore, one option for the disposal of surplus weapons Pu, amounting to more than 100t, is burning as MOX in existing LWRs.

To promote LWR MOX utilisation, there are several issues to be addressed; improved economics, higher burnup and recycling of Pu from reprocessed LWR MOX spent fuels.

The cost of MOX fuel fabrication is four to five times higher than for conventional uranium oxide fuels [5]. With the increase of MOX utilisation and thus the expanding fabrication capability of industrial MOX plants, PNC estimates that MOX fabrication costs should be reduced to less than

three times that for uranium oxide fuel. This will be achieved in fully automatic MOX plants by modifying and simplifying fabrication processes and developing more integrated equipment. Burnup increases to 55 GWd/t and beyond is another important factor for economic improvement. However, multi-recycling of Pu by reprocessing of LWR MOX spent fuels produces degraded Pu which contains more radioactive minor actinides to be transmuted and lower fissile content, requiring more protective shielding of the MOX fuel fabrication process. This will negate the efforts to save cost.

Around the year 2020 to 2030, the Pu stockpile from reprocessing will be adjusted by consuming it as LWR MOX and then the FBR will be introduced to consume recycle Pu from spent LWR MOX and provide sufficient flexibility to adjust the Pu production and consumption.

Industrial fabrication of FBR MOX fuel with higher quantities but less fissile Pu content is the next target. The fabrication technologies proven for LWR MOX fuel can be applied to FBR MOX. However, there will be strong incentives to improve safety, economics, proliferation resistance and waste minimisation by implementation of advanced technologies. The main candidates for advanced fuel technology are likely to be based on current MOX fuel recycle, because LWR MOX will still continue to be utilised in parallel with FBR MOX after around 2030.

The concept of advanced MOX fuel fabrication is closely linked to advanced reprocessing such as advanced PUREX and pyrochemical reprocessing, which aim for coextraction of Pu/U with low decontamination factors. This requires fabrication technology able to treat Pu/U/MAs in a simplified remote process without an increase in costs. One effective way to reduce MOX fuel fabrication costs drastically is the integration of recycling capability, ie the integration of fuel fabrication, reprocessing and waste treatment in one plant. Sphere-packing or vibro-packing fuel fabrication are attractive candidates; both have already been demonstrated in Switzerland and Russia and used in the UK.

International discussion and collaboration for the review and implementation of R&D for advanced fuel technologies is strongly recommended. The selection of advanced recycle technologies should be discussed widely to consider the circumstances when LWR MOX spent fuel is available for reprocessing and when the FBR fuel cycle is overtaking the LWR MOX fuel cycle; parallel LWR/FBR reprocessing plants are likely to be essential.

2.7. Partitioning and transmutation

R. Schenkel, ITU, EU

The safe disposal of highly active wastes dominates the nuclear debate in several countries, despite the fact that long term modelling calculations [6] demonstrate that the resulting maximum risk is much less than most of the risks commonly accepted by society. To further reduce the potential long-term hazard of such wastes, partitioning and transmutation (P&T) research is being performed in several countries [7,8,9] with the objective of separating the actinides and long-lived fission products then reducing their toxicity by transmutation.

Current use of MOX fuel in thermal reactors can be considered as a simple example of successful P&T for plutonium. Other toxic elements include neptunium, americium and possibly curium and technetium. Ongoing R&D activities concentrate on three major areas : partitioning, advanced fuel fabrication and transmutation.

New chemical separation processes with high separation and decontamination factors are under investigation. Extractants under test are CMPO, TRPO, DIPDA or Diamides [10]. Non-aqueous pyrochemical processes appear to be better than aqueous processes in the context of recycling and P&T applications in fast reactors; the main reasons are given in Section 2.5 (above).

147

It is clear that a fast neutron flux is essential for efficient burning of even numbered actinides and some odd numbered isotopes such as Np-237 and Am-241 [11]. Only systems with intensive high energy neutron spectra, like fast reactors or accelerator driven subcritical systems with their potential for very high neutron fluxes can effectively transmute minor actinides and long lived fission products.

How might P&T develop in future? Nuclear energy, around 2020, is expected to be provided by predominantly LWRs, some based on advanced designs. There are indications that the uranium price could increase, due to shortage of easily accessible ores, in the period from about 2020 to 2050. In such a situation, fast reactors or thorium fuelled reactor systems may become economic alternatives, [3]. This transition period of coexistence of thermal and fast reactors could be long; it may in fact be a good choice at different stages in different countries. As far as P&T is concerned, such a development could lead to the following scenarios for countries that have chosen the recycling option:

- In the medium term, the introduction of P&T could be in harmony with thermal reactor fuel cycles, i.e. predominantly based on aqueous partitioning and heterogeneous recycling in a fast spectrum waste burner. The CAPRA project could be considered a prototype for the fast burning not only of excess plutonium, but also for minor actinides. Accelerator Driven Systems fuelled by metal alloy, oxide or even nitrides could play a similar role, in particular with regard to long lived fission products.

- In the long term, the introduction of P&T could follow future reactor development. Accordingly there could be fast burners with metal, oxide or nitride fuel with minor actinide enriched cores and/or systems with self recycled fast neutron systems, i.e. in a "mixed park" concept or like for example the Integrated Fast Reactor. Fuel could be recycled on-site using pyrochemical and electrorefining technologies. In the steady state, with a conversion factor of about 1, the reactor would consume most of its own long lived waste and would only require the addition of fertile uranium or thorium as a source of fissile material.

2.8. Direct disposal

S. Bjurström, SKB, Sweden

Today, over 100,000t of used fuel is stored at nuclear power plants and interim storage facilities around the world. The world's reactors discharge another 10,000t of used fuel annually, of which around 3000t is recycled by reprocessing. Independent of the development of existing and future technologies for utilisation of this huge energy resource there is a need for storage over long periods and for permanent disposal solutions. The direct disposal technologies developed today can play an important role; a deep repository planned for direct disposal of spent fuel can retain this flexibility over long time periods with minimum burden on the future and maximum safety.

Direct disposal systems are based on deep geological disposal and the utilisation of several technical barriers to ensure safety and isolation. The advantage of such geological repositories are that many countries have suitable geology for a repository and thus the possibility of taking care of their own waste. Clay, salt, sediments and granites may all be very good host mediums for a repository. Such a repository is not technically complicated though demonstration of the safety can be complex.

The particular risk of direct disposal of used fuel is that one must deal with the properties of the fuel as they are. The potential hazard of fuel placed in a repository is related to effects "after intake" where the radioactive elements may reach the biosphere by water flows through the repository. For this, the ability of the fuel to be dissolved into groundwater obviously plays an

important role. Fission products in the fuel like caesium can be dissolved and reach the surrounding environment. However, the lifetime of those products is relatively short - some hundred years. For the long lived actinides, the potential risks will remain for much longer - many ten thousands of years before it has the same toxicity as the once-mined uranium. But, and this is very important, those products in a stable chemical form are almost impossible to dissolve and hence the source term will be very small and it is almost impossible to calculate any releases.

Spent fuel and also the vitrified waste from reprocessing must be isolated in a qualified way for several hundred years to take care of the short-lived activity. For longer periods the placement in a deep geological formation is the most important factor. There is however no reason not apply strict regulation and utilise today's good and available technology. The relatively small volumes means that much can be done within reasonable economic limits, as illustrated by the system developed in Sweden. Here safety and the isolation of fuel is based on:

- the fuel, almost impossible to dissolve in water;
- copper canister, to encapsulate the fuel in a very corrosion resistant material;
- emplacement into watertight swelling bentonite clay;
- the bedrock offering "lasting" conditions and also acting as efficient filter.

Disposal of encapsulated fuel is planned to start between 2008-2012 and continue for several decades. The technology for encapsulation is already developed on an industrial scale for a copper canister with a steel insert. A pilot plant is under construction and an application to build a commercial facility in connection with the existing interim storage is planned to be submitted some years after the turn of the century.

The deep repository is expected to be built in Sweden in a location where the geology is suitable and where there is support from the local population. The facility consists of a medium sized surface industry and underground tunnelling system at 400-500m depth where encapsulated fuel will be placed. Public acceptance is a crucial issue. Discussions are in progress with 5-10 municipalities which may be suitable for initial feasibility studies. Subsequently, investigative drilling in two locations will take place prior to selecting one for detailed characterisation in tunnels. Subject to acceptance of that particular municipality and satisfactory test results, the first phase of the repository will be constructed there.

In summary, direct disposal systems in deep repositories can offer a solution for safe storage of fuel over long periods. Such storage can - with proper preparation - be turned into a permanent solution at any time as decided by future decisionmakers. At all times there will be flexibility to accommodate new conditions and requirements and to retain the possibility to reuse the fuel (although demanding more or less work).

2.9. Waste

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One of the most complex and challenging areas of the fuel cycle is that of waste management and disposal. Waste management and disposal includes reducing the generation and diversity of wastes (waste minimisation), its retrieval, treatment, storage and ultimate disposal. Wastes include stored historic wastes generated during the early years of the nuclear industry, arisings from current plant, many of which will continue into the period 2015 to 2050, waste from decommissioning and management of redundant plant or sites and waste from advanced fuel cycle options.

The technical challenges in the waste management area include:

- Treating the large volume of historic waste.
- Devising acceptable schemes for disposing of solid wastes.
- Reducing current discharges whilst tackling the historic waste problems.
- Producing cost effective strategies that are sensitive to environmental issues.

Treating large volumes of historic waste will certainly tax the abilities of the nuclear industry. It is, however, unlikely that these tasks will demand new technological solutions, but rather they will demand skilful integration and deployment of demonstrated technologies to provide robust facilities to treat waste for disposal, with minimal discharges.

In the timeframe 2015 to 2050 it is unlikely that partition and transmutation of nuclides in waste, except utilisation of recovered actinides and ex-military material in MOX fuel, will be demonstrated and justified on economic or environmental grounds.

The main technical option is for land disposal of the current wasteforms (e.g. grouted or vitrified wastes); here the challenge is to provide a robust safety argument to support the disposal option, relying heavily on predictive tools and models underpinned with a strong scientific understanding of the local geology and problems associated with disposal.

Since disposal is currently viewed as a national or regional responsibility, past attempts to adopt an international approach by, for example deep sea dumping, have not been accepted. An international land-based repository is technically feasible in view of the relatively small total volume of higher categories of waste involved and may offer advantages where the effects of some radionuclides are not driven by inventory. Such an international approach might also offer the opportunity to utilise the best available geologies (for example, avoiding areas of seismic activity) and also offer a flexible solution for countries which cannot afford or may not need their own internal facility. Regional or international repositories seem almost inevitable.

A major issue in waste and indeed the nuclear industry is that of public perception. With the advent of freely and rapidly available information we can expect a more informed public. This is likely to result in:

- A more balanced public perception of nuclear energy in the context of competitive energy sources.

- A less emotive view of the nuclear industry with lower emphasis on our military beginnings.

- A greater understanding and less fear of the implications of radioactivity.

To play its part, the industry must put safety as its highest priority. We must also understand the public position and agenda and work with the public to address their concerns, putting our case in easily understandable terms.

Advanced fuel cycle processes will produce less waste for discharge and disposal. The concepts that are being adopted by all process industries will be applied to the nuclear industry, that is eliminating waste of all types at the process definition stage, using gentle and benign reagents, recycling and reusing material generated by processes. These activities must be pursued to balance the increased effect of treating historic wastes.

The size and scope of the challenge however demands international collaboration between existing and emerging players in nuclear energy. Standards and options require a level of international endorsement whilst the consequences and benefits of the nuclear industry transcend

national boundaries. To ensure research programmes are cost effective, international collaboration in technology development, benchmarking and sharing experiences are essential in the development of advanced fuel cycles.

3. KEY ISSUES

In the foregoing technical contributions, we have shared a vision of some of the fuel cycle technologies that may reach commercial maturity in the period 2015-2050. Though our coverage is by no means comprehensive, many issues have emerged - some technical, some institutional:

Technical

- Role of laser isotope separation when set against the evolution of advanced centrifuge technology;

- What burn-up will LWR's achieve?

- When might Fast Reactors or Thorium fuels be implemented?

- Can the advantages of non-aqueous reprocessing overturn 50 years of experience with the PUREX process?

- Is MOX reprocessing viable? What technologies may be needed to refabricate the fuel for use in FBRs?

- What are the optimum transmutation schemes and can accelerator driven subcritical systems become a reality? On what timescale?

- To what extent does transmutation reduce overall dose and is such a reduction cost-effective?

- Is it realistic to consider retrievable deep geological repositories?

- How do we balance the need to clean up historic wastes whilst reducing discharges?

Institutional

- How can we promote discussion and collaboration as a means of optimising the fuel cycle?

- How can we work together to minimise the overall cost of the fuel cycle, yet maintain commercial competition, especially in a market that historically has looked at only one sector at a time?

- How much will governments be prepared to invest in new technology?

- How do we reach agreement on international repositories?

- How do we learn to understand and communicate with the public?

- How can we retain facilities and competence in preparation for the dawning of the FBR age?

This leads to the final point; the need to retain facilities, resources, training and competence means that we can't just switch the nuclear industry 'on' and 'off'. In about 20 years we will know

for sure how serious is the threat of global warming. Nuclear appears to be the most significant contributor to retarding or even reversing planetary damage; addressing some of these issues will keep nuclear switched 'on'.

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THE DUPIC ALTERNATIVE FOR BACKEND FUEL CYCLE

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Abstract

The DUPIC[1] fuel cycle was conceived as an alternative to the conventional fuel cycle backed options, with a view to multiple benefits expectable from burning spent PWR fuel again in CANDU reactors. It is based on the basic idea that the bulk of spent PWR fuel can be directly refabricated into a reusable fuel for CANDU of which high efficiency in neutron utilization would exhaustively burn the fissile remnants in the spent PWR fuel to a level below that of natural uranium. Such "burn again" strategy of the DUPIC fuel cycle implies that the spent PWR fuel will become CANDU fuel of higher burnup with relevant benefits such as spent PWR fuel disposition, saving of natural uranium fuel, etc. A salient feature of the DUPIC fuel cycle is neither the fissile content nor the bulk radioactivity is separated from the DUPIC mass flow which must be contained and shielded all along the cycle. This feature can be considered as a factor of proliferation resistance by deterrence against access to sensitive materials. It means also the requirement for remote systems technologies for DUPIC fuel operation. The conflicting aspects between better safeguardability and harder engineering problems of the radioactive fuel operation may be the important reason why the decades' old concept, since INFCE[2], of "hot" fuel cycle has not been pursued with much progress. In this context, the DUPIC fuel cycle could be a live example for development of proliferation resistant fuel cycle. As the DUPIC fuel cycle looks for synergism of fuel linkage from PWR to CANDU (or in broader sense LWR to HWR), Korea occupies a best position for DUPIC exercise with her unique strategy of reactor mix of both reactor types. But the DUPIC benefits can be extended to global bonus, expectable from successful development of the technology.

1. INTRODUCTION

Spent fuel from PWR contains fissile remnants roughly two times higher than natural uranium. They can be separated by reprocessing or disposed of intact (i.e., the spent PWR fuel assemblies) in the geological repository. The DUPIC fuel cycle would be in fact a third alternative in-between the two conventional options in that spent PWR fuel is neither directly disposed of nor reprocessed to separate the fissile remnants in it, but that the bulk of spent PWR fuel is reformed into CANDU-compatible DUPIC fuel bundle with new cladding and appendages [1].

A precursor of the DUPIC concept would be the AIROX[3] technology developed in the early sixties by Atomics International in the USA It was destined to recycle spent LWR fuel back to LWR by addition of higher enrichment material to compensate the depleted portion in the spent fuel. Notwithstanding the difference with DUPIC in fuel form and content, a lot of its technical features are common to both fuel cycles which need remote fabrication of bulk oxides. Obviously, the AIROX concept attracted interest for its aspect of proliferation resistance in the late seventies [2], and for its possibility as an alternative to manage spent fuel in the USA [3]. There are more distant technical methods, in the family tree of fuel cycles, of remote fuel fabrication conceived for thorium oxides and metals [4].

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[1] DUPIC = Direct Use of Spent PWR Fuel in CANDU

[2] INFCE = International Nuclear Fuel Cycle Evaluation

[3] AIROX = Atomics International Reduction Oxidation

The DUPIC fuel cycle studies was initiated in the early nineties by joint efforts involving Korea, Canada and the USA The tripartite investigated technical feasibilities of the DUPIC fuel cycle including analysis of CANDU system with DUPIC fuel, comparison of various options and selection of reference process for DUPIC fuel fabrication, examination of safeguardabilities, etc. The confirmative conclusions of the feasibility study wrapped up in 1992 had lead to the next phase of the DUPIC program, experimental verification, with a target to the year 2000 in shared tasks between the tri-parties [5]. The IAEA has recently joined the program in safeguards affairs [6].

2. THE DUPIC TECHNOLOGY

A basic premise adopted for the DUPIC fuel cycle development is to minimize retrofittings that may arise in order to use DUPIC fuel in CANDU. This philosophy is based on the rationale that it would be much more cheaper and safer to fit fuel to reactor than to fit reactor to fuel. With this background, the technical question for the DUPIC fuel cycle converges to the feasibility of DUPIC fuel fabrication.

For the fabrication of DUPIC fuel, a process called OREOX[4] was selected as the most promising option, among other competing options, because it would allow maximum flexibility in fuel design satisfying the requirement of compatibility with existing CANDU system. The OREOX process is based on a thermal treatment of bulk powder of spent PWR fuel to prepare for manufacturing of pellet from which the DUPIC fuel bundle can be fabricated by remotized version of conventional technology for CANDU fuel production. Remote fabrication of DUPIC fuel will thus occupy the heart of DUPIC technology.

2.1. Compatibility with existing CANDU system

Compatibility of DUPIC fuel with existing CANDU system may be grouped in two major categories : nuclear and mechanical.

2.1.1. Nuclear compatibility

Spent PWR fuel from PWR contains fissile remnants around 1.5% depending on burnup attained in PWR. This is roughly two times higher than natural uranium which is used for fresh CANDU fuel. This is a theoretical indication that the DUPIC fuel could be burnt two times longer in a CANDU of equivalent output than natural uranium fuel. Frequency of fuel replacement will have to be adjusted accordingly.

Major technical considerations for DUPIC fuel use in CANDU have been in analyses since the feasibility study. The neutronic and thermohydraulic compatibilities are integrated into the homogeneity of DUPIC fuel composition. As there are a variety of PWR fuel burnups resulting in compositional differences, consideration is given to the preparatory selection for batch mixture in such way to fabricate DUPIC fuel of homogeneous composition.

A lot of efforts are also focused on the analysis of safety margins in CANDU and on the adjustment of control factors therefrom in the use of DUPIC fuel with reference to natural uranium fuel use. [7]

2.1.2. Mechanical compatibility

Concerning the feasibility of DUPIC fuel handling, both for charge and discharge, it was found that the existing refueling machine could be used for DUPIC fuel loading into the fuel channel in

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[4] OREOX = Oxidation and Reduction of Oxide Fuel

reverse sequence to the current handling of spent fuel discharged from the core. A minor addition of lifting mechanism seems to be needed, nevertheless, down in the spent fuel bay in order to move the DUPIC fuel up to refueling position because the current spent CANDU fuel handling system is designed only to slide down spent fuel.

2.2. Feasibility of DUPIC fuel fabrication

There are various methods to transform spent PWR fuel to CANDU type DUPIC fuel. They can be categorized into two technical groups : mechanical reconfiguration and powder conditioning, after decladding, for pellet formation or vibratory packing (vipac). The comparative assessment of these optional methods, during early feasibility study of the DUPIC program, concluded that the latter is preferred mainly for the reason of fuel compatibility as explained previously. Among the latter category, powder-pellet route was preferred mainly due to its wide commercial experience although the other option (vipac) may have advantages in remote fabrication due to its simpler process.

For the powder conditioning for pellet fabrication which has been adopted as reference process for development and test of DUPIC fuel, the OREOX process uses repeated oxidation and reduction to make the bulk powder more apt to pellet formation and sintering. Once pelletized, the rest of the processes to produce DUPIC bundle is not much different from conventional processes for CANDU fuel fabrication [8].

The radioactive wastes arising from DUPIC fuel fabrication are mainly non-fuel bearing structural materials removed from disassembly of spent PWR fuel and decladding and off-gases released from OREOX and sintering processes. These wastes can be treated and managed by existing technologies, except the semi-volatile gases for which special trapping methods are being developed in the DUPIC program.

As remarked above, all the processes involved in the DUPIC fuel fabrication must be performed remotely in biological shielding and containment to protect the workers from radiation hazards. The remote systems feature of the DUPIC fuel fabrication would require a new dimension in technological efforts and costs. This is just the penalty to the enhanced safeguardability of the radioactive process. This new direction, however, is convergent to the recent technical trend toward increasing automation in the manufacturing industry to reduce labor costs and risks.

2.3. Safeguards

The DUPIC fuel fabrication is resistant to proliferation not only because it involves no separation of fissile material but also because the heavy shielding enclosing the radioactive process act as a barrier to diversion possibility. Similar technical principles have attracted considerable attention especially during the seventies when measures to enhance safeguardability of conventional reprocessing were looked for by such methods as low-decontamination or denaturing special nuclear materials with radioactive spikants. An extension of such principles is resumed recently as "spent fuel standard" by the National Academy of Science of the U.S. as a key security criterion for judging options for weapon plutonium disposition [9].

In the DUPIC program, systems for containment and surveillance are being developed to augment the safeguardability of DUPIC fuel fabrication. A recent outcome of this developmental efforts is an instrument that can measure fissile content in the spent fuel material with enhanced accuracy [10].

3. BENEFITS OF THE DUPIC ALTERNATIVE

The DUPIC alternative as a proliferation resistant fuel cycle concept offers a multiple benefits that are expectable from PWR-CANDU synergism in comparison with once-through option. Such benefits are maximized at a reactor a ratio between 3 PWRs and 1 CANDU (depending on burnup). At this optimal ratio, up to 30% saving in natural uranium possible. Another advantage, more significant in today's perspective, is the multiple reduction in spent fuel arising by removal of spent PWR fuel and by the doubling burnup in CANDU. Corollary to this quantity reduction to about one-third in comparison once-through, it was also revealed that there would be a "quality effect" of radiotoxicity reduction at long-term by DUPIC in the final disposal of spent fuel [11].

Regarding the DUPIC economics, a study in the DUPIC program has indicated that the DUPIC alternative can be competitive with once-through, as well as other recycle options taking the synergetic effects into account [12].

4. INTERNATIONAL DUPIC LINK

The DUPIC fuel cycle concept is characterized by burning spent PWR fuel again in CANDU, without separating any fissile material, taking advantage of high neutron economy of heavy water reactors. It requires therefore a reactor mix PWR-CANDU, which Korea adopted coincidentally. The possibility of DUPIC fuel linkage from LWR to HWR is not, however, limited to mixed reactor counties like Korea : it can be extended to countries of LWR or HWR by international cooperation if such linkage is agreed between the interested countries.

5. CONCLUSION

The DUPIC fuel cycle is an emerging alternative in fuel cycle backend for synergism between PWR and CANDU (and between LWR and HWR, in general). A conspicuous feature of the DUPIC fuel cycle concept is, among others, the proliferation resistance which is unique in its kind. Other benefits include not only saving of natural uranium for CANDU fuel, but also removal of spent PWR fuel that would be transformed into DUPIC fuel to give two times higher burnup in CANDU, thus contributing to more power production without additional burden to the environment. The developmental efforts are now in full swing, under international cooperation frame, in anticipation of multiple benefits on national and international level.

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SESSION IV

RISK ASSOCIATED WITH THE TRANSPORT OF RADIOACTIVE MATERIALS IN THE FUEL CYCLE

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Abstract

This paper sets out the regulatory framework within which nuclear fuel cycle materials are transported. It establishes the basic principles of those safety regulations and explains the graded approach to satisfying those requirements depending on the hazard of the radioactive contents. The paper outlines the minimum performance standards required by the Regulations. It covers the performance standards for Type C packages in a little more detail because these are new to the 1996 Edition of the IAEA's Regulations for the Safe Transport of Radioactive Material and are less well reported elsewhere at present. The paper then gives approximate data on the number of shipments of radioactive materials that service the nuclear fuel cycles in France, Germany and the UK. The quantities are expressed as average annual quantities per GW_{el} installed capacity. There is also a short discussion of the general performance standards required of Type B packages in comparison with tests that have simulated specific accident conditions involving particular packages. There follows a discussion on the probability of packages experiencing accident conditions that are comparable with the tests that Type B packages are required to withstand. Finally there is a summary of the implementation of the Regulations for sea and air transport and a description of ongoing work that may have a bearing on the future development of mode related Regulations. Nuclear fuel cycle materials are transported in accordance with strict and internationally agreed safety regulations which are the result of a permanent and progressive process based on social concern and on the advancement of knowledge provided by research and development. Transport operations take place in the public domain and some become high profile events in the management of these materials, attracting a lot of public, political and media attention. The risks associated with the transport of radioactive materials are low and it is important that nuclear fuel cycle materials are managed in accordance with their actual rather than their perceived hazard. Transport is a vital component in the management of nuclear fuel cycle materials but it should not have an undue influence in the choice of fuel cycle strategies.

1. INTRODUCTION

This paper sets out the regulatory framework within which nuclear fuel cycle materials are transported. It establishes the basic principles of those safety regulations and explains the graded approach to satisfying those requirements depending on the hazard of the radioactive contents. The paper outlines the minimum performance standards required by the Regulations. The paper then gives some data on the kind and quantities of shipments of radioactive materials that are needed to service the nuclear fuel cycles in France, Germany and the UK. There is also a short discussion of the IAEA test requirements for Type B packages and on the probability of packages experiencing accident conditions that are comparable with the tests that packages are required to withstand. This is followed by a discussion of the performance of some real packages under accident conditions and estimations of risks associated with shipments of spent fuel. Finally there is a summary of the implementation of the Regulations for sea and air transport and a description of ongoing work that may have a bearing on the future development of mode related Regulations.

2. REGULATORY FRAMEWORK

Since 1961, the International Atomic Energy Agency has published *Regulations for the Safe Transport of Radioactive Materials* [1]. These Regulations have been adopted by or are used as the

basis for national regulations by Member States of the Agency, and have been incorporated into regulatory documents promulgated by a number of international organisations. Compliance with these Regulations has proved to be effective in minimising the risks associated with transporting radioactive material. The excellent safety record has not stopped the Regulations being further improved and the Regulations have undergone comprehensive revisions in 1973, in 1985 and most recently in 1996. This approximate ten year cycle of revision has been argued to represent an appropriate balance between the need for regulatory stability and the need to keep abreast of scientific and technical developments such as those in radiological protection.

3.   OTHER RELATED CONVENTIONS AND REGULATIONS

This paper deals with transport safety, but it is important to realise that the Regulations are part of a framework containing other guidelines and conventions that have a bearing on transport. Guidelines for protecting nuclear material against sabotage and theft are given in the IAEA report on *Physical protection of nuclear material* [2] and in the *Convention on the physical protection of nuclear material* [3]. The Convention concerns specifically the international transport of nuclear material. International co-operation is essential when countries are affected by transport accidents. Such accidents or incidents occurring in international waters or air space will be of interest internationally. Additionally, events happening within national borders can have implications for neighbouring countries. In recognition of these concerns the Agency has prepared two Conventions: The *Convention on early notification of a nuclear accident* [4] and the *Convention on assistance in the case of a nuclear accident or radiological emergency* [5]. In the event of an accident, the question of liability is covered by two basic international regimes on nuclear third party liability. These are the so-called Paris [6] and Vienna [7] Conventions which are linked via a Joint Protocol [8].

4.   BASIC PRINCIPLES OF PACKAGE DESIGN

The objective of the Regulations for the Safe Transport of Radioactive Material is to protect persons, property and the environment. This protection is achieved by requiring:

1.   Containment of the radioactive contents;

2.   Control of external radiation levels;

3.   Prevention of criticality;

4.   Prevention of damage caused by heat.

Concept of the package

A cornerstone of the Regulations is that safety is built-in to the design of the package. The package is a system that comprises the sum of two parts; namely the packaging and the contents. To attain equivalent safety, if less reliance is placed on one part of the system then more reliance must be placed on the other. It stands to reason that when significant quantities of radioactive material is transported as either a liquid, gas or as a powder very stringent demands will be placed on the containment system of the packaging. If such radioactive material is transported as a metal or as a ceramic or other solid, part of the containment can be argued to be the material itself backed-up by the containment features of the packaging.

5. GRADED APPROACH

The requirements are satisfied firstly by applying a graded approach to content limits for packages and conveyances and to performance standards that are applied to package designs depending on the hazard of the radioactive contents.

The 1996 Edition of the Regulations which is planned to be effective from 2001 provides for five primary types of package. These are:

1.   excepted packages

2.   industrial packages

3.   Type A packages

4.   Type B packages

5.   Type C packages

Excepted packages

Excepted packages are those containing quantities of material that are so small that they are excepted from most design and use requirements. However, they must meet certain requirements to ensure that they can be readily identified and safety transported.

Industrial packages

Industrial packages are used to transport materials known as low specific activity (LSA) materials and surface contaminated objects (SCO). LSA materials have small levels of radioactivity per unit mass and some non-radioactive objects having low levels of surface contamination may meet criteria to qualify as SCO's. Both of these categories of radioactive material have intrinsically low levels of risk. Therefore, because of their low hazard, they do not require packaging that is able to withstand accident conditions of transport.

Type A packages

Type A packages are intended to provide a safe, economical means for transporting relatively small quantities of radioactive material. Such packages are expected to retain their integrity when subjected to normal conditions of transport such as being dropped during handling, being struck by a sharp object, having heavy cargo stacked on top or being exposed to rain. The Regulations specify the maximum amount of radionuclides that can be loaded into such packages. These limits ensure that in the event of a release in an accident the risks from both external radiation and contamination are low.

Type B packages

Type B packages are used to transport large amounts of radioactive material. To maintain a low level of risk, these packages are required to withstand accidents. Each design must be approved

163

by the competent authority of the country in which the package was designed. Type B packages must be shown to withstand tests that simulate severe accident conditions such as impact, crush, penetration , fire and immersion. For surface modes of transport (road, rail, sea and inland waterway) the content limits are specified in the certificate of approval for the design of the package. In the 1996 Edition of the Regulations a content limit for Type B packages transported in an aircraft has been imposed. This reflects the outcome of an international consensus on packaging standards for carrying large quantities of radioactive material by air. Also, the 1996 Edition introduced a stringent specification for low dispersible material (LDM) which, if met and approved by the appropriate competent authorities, will allow those materials to continue to be carried in large quantities by air using a Type B package. This restriction on the use of some Type B packages travelling by air is expected to come into force on 1 January 2001, on implementation by the International Civil Aviation Organisation (ICAO).

Type C packages

The requirements for Type C packages were introduced to the 1996 Edition of the Regulations for the air transport of large quantities of radioactive material. The need for Type C packages was driven largely by the recognition that air accidents, although rare, can be more severe than accidents occurring in surface mode transport, especially with respect to impacts. The tests for Type C packages are considerably more onerous than those applying to Type B packages. Again, each design of package must be approved by the competent authority of the country in which the package was designed.

6. PACKAGE PERFORMANCE TESTS

The following paragraphs summarise the test requirements. For brevity, some aspects are not reported in this section. The performance tests introduced into the 1996 Edition of the Regulations for Type C packages are described in more detail as these are new and less well reported elsewhere at present.

Tests to withstand normal conditions of transport

Packages that are designed to withstand minor accidents and incidents that may occur during transport must pass the following tests without a loss of contents or significant increase in external radiation hazard:

1.   the water spray test

2.   the free drop test (from a height of up to 1.2 m)

3.   the compression test and

4.   the penetration test

Tests to withstand accident conditions of transport

Surface modes

Packages that are designed to withstand accidents must undergo the following tests, after which they must be shown to retain their radioactive contents and shielding properties within defined limits:

1. Dropped from 9 metres onto an effectively unyielding target so as to suffer maximum damage (the impact speed is 13.3 metre/second);

2. Dropped from 1 metre onto a metal steel bar, 15 cm in diameter;

3. Subjected to an engulfing 800°C thermal test for 30 minutes; and

4. Immersion in water to a depth of at least 15 metres (200 metres for irradiated fuel flasks).

Air mode

Packages that are designed to withstand aircraft accidents are required to undergo the following cumulative test sequences, after which they must be shown to retain their radioactive contents and shielding properties within defined limits.

Sequence 1 (to be carried out in the given order on the same specimen) in which the specimen is:

1. Dropped from 9 metres onto an effectively unyielding target so as to suffer maximum damage (the impact speed is 13.3 metre/second);

2. Subjected to dynamic crush by placing it on the same unyielding target, in the worst orientation, and dropping a 500 kg plate onto it from a height of 9 metres;

3. Subjected to a puncture/tearing test by dropping it from 3 metres onto a conical probe; and

4. Subjected to an engulfing 800°C thermal test for a period of one hour.

This test sequence recognises that it is possible for a long duration (1 hour) fire to occur following a low speed impact with subsequent crushing and puncture/tearing.

Sequence 2 (this may be carried out on a separate specimen from sequence 1) in which the specimen is:

1. subjected to an impact at a speed of 90 metre/second onto an essentially unyielding target so as to suffer maximum damage

A separate specimen may be used for this test because exposure to long duration fires in the aftermath of a high speed impact is highly unlikely. The fuel on board the aircraft will be dispersed in the crash and will not form pools to supply long lasting fires. The impact speed of 90 metres per second was derived from data on jet aircraft crashes collected for analysis by the Lawrence Livermore National Laboratory in the USA .

Additionally, these packages must be shown to meet the same containment and shielding criteria as those above when subjected to burial and must be shown not to rupture when immersed in 200 metre deep water. The requirement to demonstrate the ability to withstand burial is done by assessment assuming the package to be undamaged, buried in dry soil at 38 °C in a steady state condition. The burial test was introduced because packages involved in high speed crashes may be covered by debris or buried in soil. If packages whose contents generate heat become buried, an increase in package temperature and internal pressure may result.

7. QUANTITIES AND CHARACTERISTICS OF SHIPMENTS

A salient feature of electric energy production by nuclear power is the high energy concentration in the fuel compared to all other energy sources. This fact has a large influence on the amounts of radioactive materials requiring transportation within a fuel cycle. The volume of shipments in relation to the produced electric energy is therefore low. Typical average annual quantities of radioactive materials expressed in tons or m^3 to be shipped per 1 GW_{el} installed electric power are summarised in Table 1 for light water reactors:

TABLE I: TYPICAL AVERAGE ANNUAL QUANTITIES OF RADIOACTIVE
MATERIALS PER 1 GW_{EL} INSTALLED ELECTRIC POWER

Material	Shipped quantity per year and 1 GW_{el}	Approximate number of transport units
Uranium ore	80000 t	2700 vehicle loads
Uranium concentrate U_3O_8	200 t (HM)	17 containers
Uranium hexafluoride UF_6	200 t (HM)	25 cylinders
Uranium hexafluoride UF_6 enriched	25 t (HM)	17 cylinders
Fresh fuel assemblies (UO_2, MOX)	25 t (HM)	4 vehicle loads
Spent fuel assemblies	25 t (HM)	5 spent fuel casks
Operational low to medium level waste	200 m^3	50 containers
Reprocessing		
Plutonium oxide	0.2 t	8 packages
Low level reprocessing waste	80 m^3	20 containers
A-containing reprocessing waste	60 m^3	15 containers
Vitrified high-level waste	3 m^3	1 HAW flask

The numbers given in Table 1 are to be understood as approximate values. For several reasons the quantities to be transported have experienced reductions in the past and are still being reduced. Reasons are for instance higher burn-up and associated higher enrichment of UO_2 and MOX fuel elements, improvements leading to reduced quantities of operational wastes in nuclear facilities, waste volume reduction by improved waste conditioning techniques. Direct disposal of spent fuel without reprocessing would in addition lead to about 25 m^3 of low-to medium level waste from conditioning of the spent fuel elements. Concerning the transportation of the various radioactive materials of Table 1 a few remarks are made:

- Due to the low U content of uranium ore the quantities to be shipped are comparatively large. The material is shipped as Low Specific Activity material (LSA-I) with few regulatory requirements which reflect the low radiological hazard potential.

- The hazard of UF_6 transports is largely dominated by the chemical compared with the radiological hazard. Two types of transport containers are widely used, the 30 B and the 48Y containers carrying about 2.3 and 12 tons of UF_6 respectively. The last revision process of the IAEA Transport Regulations has resulted in increased requirements for such packages, especially concerning the thermal insulation of the contents to prevent dangerous pressure build-up in case of severe fires. A Co-ordinated Research Programme (CRP) has been undertaken by the IAEA to develop accurate, validated analytical codes for calculating the thermal response of standard shipping cylinders containing UF_6. In this respect the results of the French-Japanese Tenerife program which is being carried out in France with partial support by the European Union and which combines large scale experiments and analytical modelling are of special importance.

- The transport of fresh enriched fuel assemblies of UO_2 requires Type AF packages being essentially Type A packages with additional requirements which take into account that the material is fissile. In the case of fresh MOX fuel elements Type B packages are required. The annual supply of a large nuclear power plant of approximately 25 tons can e.g. be shipped by four truck loads. Enhanced requirements concerning air transport of unirradiated MOX fuel will have to be applied as soon as the 1996 Edition of the IAEA Transport Regulations has been implemented for the air mode.

- On average per GW_{el} installed power annually about 20 tons [heavy metal (HM)] of spent fuel have to be shipped. Due to the high contents of fission products, the presence of larger amounts of actinides, the high thermal power and radiation field the transport packages have to fulfill very high safety requirements. Modern casks have payloads of several tons up to around 10 tons of HM. Therefore the annual number of transport casks with spent fuel associated with 1 GW_{el} installed power is limited to some units.

- The quoted volume of 200 m³ of operational radioactive waste which is predominantly of low level encompasses operational wastes arising in fuel fabrication and nuclear power plants. Improvements in operational procedures and in waste management have lead to reductions of waste volumes in recent years. In many nuclear power plants, typical annual conditioned waste volumes are in the range of 60 m³ per 1 GW_{el}.

- Reprocessing leads to recovery of Pu and U from the spent fuel. About 0.2 tons of Pu per 1 GW_{el}, in most cases in the form of oxide powder have to be shipped from the reprocessing plant to a MOX fuel fabrication plant. In France the FS-47 package is used having a capacity of 17 kg of fissile Plutonium and an overall weight of 1.5 tons. One shipment comprises in general 10 FS-47 packagings licensed as Type B(U)F in France, Germany, Belgium and Japan. They are generally loaded inside an internal rack which accommodates the packagings inside a special container which is mounted on a purpose built truck. The package has to fulfill the requirements of Type B fissile packages but have been demonstrated to withstand accidents environments far beyond the IAEA test conditions. Few transports are annually needed per 1 GW_{el} installed power for the shipment of PuO_2 powder from reprocessing of spent fuel.

- Operational waste arising from reprocessing has been and is still being reduced due to process improvements. The larger fraction is low level waste with low a-content, a smaller part contains appreciable quantities of a-emitting radionuclides and represents medium level waste. Transport containers used for the shipment of such waste being predominantly LSA material have payload volumes of up to 10 m³. Assuming an average waste volume of 4 m³ per container would lead to an annual number of about 35 containers of such waste to be shipped to interim storage or final disposal per 1 GW_{el} installed power.

167

- The high level vitrified waste from reprocessing is contained in primary steel canisters of 175 l inner volume which are transported in casks similar to spent fuel casks which hold up to 28 such canisters. Therefore the shipment of one such cask is enough to transport this kind of waste from one year reactor operation at 1 GW_{el} installed power.

8. DISCUSSION OF TEST REQUIREMENTS FOR TYPE B PACKAGES

The drop of a package from a height of 9 m onto the required unyielding target is equivalent to an impact velocity of 48 km/h. It is immediately evident that accidents in road and rail traffic can happen at much higher impact speeds. This fact has raised concern in the public about the adequacy of this test condition. The important point is that the required unyielding target of the drop test represents severe impact conditions. Unyielding target means that practically all of the available kinetic energy is acting onto the package and is not dissipated to some extent by deformation or destruction of the target. The interaction between the package and the target is determined by the package properties in relation to the target properties. Especially for the very heavy and strong packages like spent fuel casks, a very large fraction of the energy will be absorbed in and dissipated by the impacted surface and other structures such as those of the conveyance. This has been illustrated in many spectacular tests performed to simulate improbable accidents that might appear to exceed the IAEA test conditions for Type B packages.

A similar discrepancy exists between perceived and factual severity of the fire test which is to be performed with the identical Type B package following the mechanical tests: The package has to be subjected to a fully engulfing fire of 30 minutes duration and a temperature of at least 800°C. The crucial quantity is the thermal energy input to the package and therefore the combination of all three fire test requirements is important. Especially in the case of large packages as used for the transport of spent fuel elements or high level vitrified waste considerable experimental effort is needed to reach all three required test conditions. Real fires involving large containers are predominantly not fully engulfing and result even in the case of temporary higher flame temperatures or longer fire duration in much lower heat input to the package.

The relationship of the mentioned test conditions for Type B packages to realistic or conceivable transport accidents is unfortunately not immediately evident. For that reason research projects and studies are being performed to quantify more clearly the safety margins generated by the regulatory test.

Various studies have compared mechanical and thermal loads to packages according to the Type B test conditions with real accident situations. A study performed in the USA for the Nuclear Regulatory Commission 10 years ago [9] concluded on the basis of detailed analyses incorporating various conservative elements that 99.4 % of all truck accidents and 98.7 % of all rail accidents involving spent fuel casks would have both mechanical and thermal loading conditions less than those implied by the Type B test conditions. These results are in support of the intention of the IAEA test requirements which aim to cover a high percentage of real life mechanical and fire accident impacts. In addition, it should be mentioned that accident loads which exceed the test conditions would in general not result in a significant reduction of containment capability of the packaging or a significant release of radioactive matter due to the built-in safety reserves beyond the test loads.

9. TESTS WITH VERY SEVERE ACCIDENT IMPACTS

Especially with packages designed for the carriage of spent fuel, vitrified high level waste and plutonium, e.g. in the form of PuO_2 powder or fresh MOX fuel elements various experiments have been performed to simulate severe accident environments. A few tests to study the package behaviour under conceivable but highly unlikely accident conditions will be shortly mentioned:

In 1984 a severe accident situation involving a flask for Magnox spent fuel was experimentally investigated in UK [10]. The postulated situation was as follows: as consequence of a preceding accident a railcar loaded with a flask for spent fuel derailed, turned over and came to rest in an unfavourable orientation on the adjacent tracks. An approaching train runs with high speed into the flask. In this experiment a 140 tons diesel engine followed by three passenger cars collided at a speed of 160 km/h with the flask in such a way that the mechanical impact and the strain to the lid-flask body junction was maximised. Detailed analyses preceded this experiment, e.g. to predict the mechanical loads to the flask and to the train. The event sequence was filmed with many high-speed cameras and the flask was equipped with various measuring devices in order to compare observed and predicted impact loads.

The transport flask retained its full integrity even if it experienced minor localised deformation of a few external cooling fins. The engine, on the other hand, with its much lower rigidity in comparison to the flask was heavily deformed and damaged. For this low probability accident predicted and observed results of the test compared well and showed the forces acting onto the flask during the impact were only about half of those experienced in the 9 m drop test onto an unyielding target.

Similar tests to simulate very severe accident environments have been performed in the USA at Sandia National Laboratories. For instance, a truck loaded with a cask for spent fuel ran into a massive concrete wall at a speed of 130 km/h [11]. This test resulted in severe destruction of the truck but no reduction of containment function of the cask.

In Germany a postulated crash of a fast flying military jet into a CASTOR type spent fuel cask was investigated [12]. A cylindrical body of 1 ton weight simulating the turbine of the jet was shot with a special gun at a speed of 1080 km/h onto the side and the lid of the cask. Damage to the cask wall resulted in localised deformation of some cooling fins, impact onto the lid led to some deformation and associated reduced but nevertheless acceptable leak tightness.

In France and UK packages and prototype packages for the transport of PuO_2 were tested beyond the regulatory requirements and showed safety reserves. To confirm all these favourable results it is important to develop and promote R and D projects to evaluate in a more systematic manner the margins of safety.

10. TRANSPORT ACCIDENT RISK

Over the past 40 years transport operations with radioactive materials have had an excellent safety record but incidents and accidents which may lead to a release of significant quantities of radioactive materials cannot be totally excluded. The risk from such events is determined by the probability or frequency of accidents which lead to a release of radioactive material into the environment and the resulting radiological consequences such as radiation exposure of persons or contamination of the environment. Of special concern in this respect are transports of spent fuel, of vitrified high level waste and of large amounts of Plutonium in various forms. The reasons are that shipments of spent fuel and vitrified waste contain very large quantities of radioactive material, whereas in the case of Plutonium shipments it is more the high radiotoxicity of Plutonium if it becomes airborne as particulate matter and is in a respirable particle size range (< 10 mm aerodynamic diameter). The statistical nature of such accident events can be best analysed using the technique of probabilistic risk assessment. Risks can be quantified per distance travelled, or on an annual basis. Such assessments call for a lot of information:

● Probability or frequency of accidents of a given severity;

● Behaviour of the packaging and radioactive contents to determine release fractions;

- Determination of physical and chemical form of released material;

- Dispersion modelling;

- Radiation exposure and consequence modelling.

The results are generally presented as frequency distributions which correlate the radiological consequences and the expected probabilities of occurrence.

Such kind of studies have been and are being performed by many institutions in a number of countries. GRS and IPSN, for instance, have made comprehensive studies of the transport risk associated with waste transports to operating or planned final waste repositories [13, 14]. In a common study of both institutions which was partially funded by the European Union the transport risks of return shipments of high level vitrified waste and of bituminized waste from reprocessing German spent fuel in France have been quantified [15].

The mentioned and other studies came to the conclusion that the risk of radioactive material transports is low. These findings are in accordance with the world-wide safety record observed in this domain over the past 40 years. As an illustration, an estimate is given here concerning the accident risk of spent fuel transport in the three countries France, Germany and UK: In the context of the Konrad Transport Study [13] conducted by GRS the goods train accident statistics of the German railways of a ten year period was analysed. This lead to a value of about 1 railcar accident per 10^8 km with damage to the railcar exceeding a lower limit of 3000 DM. According to the cited US NRC study [9] about one in a 100 railway accidents could result in mechanical and/or thermal impact to a spent fuel package of severity comparable to the IAEA test conditions.

Originating in the three countries there are annually about 1000 transports of spent fuel: about 200 in France, 80 in Germany and about 700 in UK (Magnox and AGR spent fuel). Assuming an average transport distance by rail of 700 km leads to an expected frequency of $7 \cdot 10^{-5}$ per year (1000 transports per year $\cdot$ 700 km $\cdot$ 10^{-10} severe accidents/railcar-km). This value is equivalent to a statistical average of one accident event in 14000 years with severe impact onto a spent fuel package if one assumes continuous transport operations at the present level in the three countries. Due to the safety margins of spent fuel cask above the regulatory requirements even under such accident conditions radiologically significant releases of radioactive material are not to be expected.

11. MODAL ASPECTS

The IAEA's Regulations take the form of recommendations to Member States. However, they are incorporated by modal international organisations into their regulatory documents. As examples, the International Civil Aviation Organisation use the Regulations in its Technical Instructions [16] and the International Maritime Organisation (IMO) adopt them into its International Maritime Dangerous Goods (IMDG) Code [17]. Many Member States use these modal documents as the basis of Regulations governing international shipment of dangerous goods and in due course adopt those same rules for domestic shipments as well. At present the 1985 Edition of the Regulations (As Amended 1990) are used as the regulatory basis for shipping radioactive material. There is now underway a concerted effort among the international organisations to implement the 1996 Edition of the Regulations for international shipment from 1 January 2001.

In November 1993, the Assembly of the IMO adopted a *Code for the safe carriage of irradiated nuclear fuel, plutonium and high-level wastes in flasks on board ships (INF code)* which was developed jointly by the IMO, IAEA and the United Nations Environment Programme. It applies in addition to the IAEA Regulations and the IMDG Code where it is published as a supplement. The

purpose of the Code is to ensure adequate fire protection of the cargo spaces used for the carriage of INF material and that adequate damage stability of the ships carrying INF was provided by appropriate IMO regulation, particularly for the case of non-purpose built ships.

In the context of package design requirements used for radioactive materials, and under the auspices of the IAEA, research is being conducted into accident severity at sea and also in the air mode. If sound evidence shows that a more severe accident environment exists for these modes of transport than already encompassed by the IAEA package design requirements and associated tests then the IAEA will consider strengthening the packaging requirements and tests within its continuous review of its Regulations.

12. CONCLUSIONS

Nuclear fuel cycle materials are transported in accordance with strict and internationally agreed safety regulations which are the result of a permanent and progressive process based on social concern and on the advancement of knowledge provided by research and development. Transport operations take place in the public domain and some become high profile events in the management of these materials, attracting a lot of public, political and media attention. The risks associated with the transport of radioactive materials are low and it is important that nuclear fuel cycle materials are managed in accordance with their actual rather than their perceived hazard. Transport is a vital component in the management of nuclear fuel cycle materials but it should not have an undue influence in the choice of fuel cycle strategies.

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RADIOACTIVE MATERIAL RELEASES IN THE NUCLEAR FUEL CYCLE - RECENT EXPERIENCE AND IMPROVEMENTS

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Abstract

The nuclear fuel cycle involves a wide range of activities and technologies from the mining of uranium, to the production of electricity and radioisotopes for medical and industrial applications, to the reprocessing and recycling of used fuel, to decommissioning and waste disposal. Worker exposures and releases to the environment are carefully controlled in: (a) all stages of uranium mining, refining and fuel fabrication, where occupational exposures and releases have decreased while production has increased; (b) the operation of nuclear power plants, where occupational exposures and releases have decreased as reactor vendors evolve their products and reactor operators optimize their procedures; (c) fuel reprocessing facilities in the U.K. and France, where occupational exposures and releases have decreased while the amount of fuel processed has increased; and in (d) decommissioning nuclear facilities and waste management activities. The nuclear industry's recent record of achievement in controlling its releases and ensuring the radiological protection of its employees has been excellent. It is clear that releases and occupational exposures from modern nuclear facilities of all types contribute negligibly to the radiation environment to which all biota are exposed. But the general public seems not to appreciate the low environmental impact of nuclear activities. The future of nuclear power and of other applications of nuclear technology—applications in medicine, in agriculture and in industry—will depend on maintaining a high standard of performance so that the public and decision makers can be assured that the industry is safe.

1. INTRODUCTION

Commercial nuclear power plants have been in operation for over 40 years. The nuclear industry can now be considered to be a relatively mature industry, notwithstanding that significant improvements and advances continue to be made and that the widespread deployment of advanced fuel cycles is yet to be realized. Since its inception, the nuclear- power- industry has recognized the potential hazards posed by its radioactive products and by-products. In response, it has acted to control the release of radioactive effluents and occupational exposures, and hence to protect public and worker safety and the environment. In comparison with the chemical industry, zero release has not been, at least historically, a goal. Three factors contributed to the industry's approach:

- the existence of the International Commission on Radiological Protection (ICRP) which had established a framework for radiation protection (see for example references 1 and 2);
- the existence of naturally occurring radiation fields to which we are all exposed; and
- the existence of anthroprogenic radioactivity from fallout from the atmospheric testing of nuclear weapons.

173

Thus, limits were established for releases based on the concept of risk to the public and plants were operated to keep releases at a fraction of the allowable limits. Similarly, occupational dose limits were established so that the risk of death from occupational exposures would not exceed the risks associated with working in a 'safe industry.' With time, the radiation-protection framework has changed so that, today, ICRP limits are treated as maximum values and releases and exposures are kept as low as reasonably achievable, social and economic factors taken into account (the ALARA principle) [2]. As well, dose limits for both occupational exposures and public exposures have decreased over time.

The nuclear fuel cycle involves a wide range of activities and technologies from the mining of uranium, to the production of electricity and radioisotopes for medical and industrial applications, to the reprocessing and recycling of used fuel, to decommissioning and waste disposal. In all these activities control of releases and of occupational exposures has been and continues to be an important objective and the nuclear industry's record of achievement in controlling its releases and ensuring the radiological protection of its employees has been, with some exceptions, excellent. This paper summarizes the performance achieved in recent years.

2. URANIUM MINING, REFINING AND FUEL CONVERSION

2.1. Introduction

As with all nuclear operations, worker exposures and releases to the environment are carefully controlled through all stages of uranium mining, refining, and fuel fabrication. It is well known that experience in countries of the former east bloc and early experience in Canada, the U.S.A. and elsewhere have caused radiation-induced illness (lung cancer) and environmental degradation, severe degradation in some cases. But it is not the purpose of this paper to review this experience. Rather, the aim is to reflect the status of the modern industry and so we have chosen to summarize recent Canadian experience as representative of this status. Brief mention is made, however, of cleanup efforts being made to address problems arising from past practices.

The current Canadian uranium industry comprises the following activities: uranium mining in northern Saskatchewan, which produces about 30% of the world's supply of uranium, in the form of yellowcake (chemical concentrate); refining at Blind River, Ontario, where yellowcake is purified by solvent extraction producing UO_3; conversion at Port Hope, Ontario, where UO_3 is converted to UO_2 for the CANDU programme and to UF_6 for enrichment for use in LWRs; and fuel fabrication for the CANDU programme at facilities in Port Hope, Toronto and Peterborough, Ontario [3].

2.2. Mining and milling

Past mining practices have used conventional mining methods, both underground and open pit. The new generation of mines are deep underground, with high-grade ore bodies, most notably McArthur River and Cigar Lake, which average more than 10% U. These higher grade deposits have the potential for significant radiation exposures. In the past, radon progeny have been the principle source of radiation exposure for miners, but the new deposits produce significant gamma radiation fields and ore dust may also be an important exposure source. In addition, mine water can carry dissolved radon into mine openings, where it is released to add to the radon progeny problem. The new developments are designed for non-entry mining, whereby the miners never enter the stope thus reducing the potential for exposures. Eagle Point is already in production using such techniques. Here, development is done in waste rock, the stope is drilled and blasted from above and the ore is removed from below with a remote-controlled scoop-tram [4].

Two approaches are being taken for milling the very high-grade ores. Cigar Lake ore will be milled at McClean Lake in small vessels in a shielded facility. McArthur River ore will be transported

174

to Key Lake and blended with low-grade Key Lake material. This will reduce the radiation fields and also permit recovery of uranium from the low-grade rock, which otherwise would be uneconomical and present a decommissioning problem. Uranium mills have much less of a problem with radon progeny than do the mines, but gamma radiation doses are similar and there are more potential sources of dust exposure. In addition to ore dust from crushing and grinding, there is also the potential for inhalation of yellowcake dust.

The use of non-entry mining, increased mine ventilation, grouting and freezing to control water (and reduce radon transport), shielding of equipment, shielding of mineralized veins in the walls of travelways, and the use of continuous radiation monitoring equipment at strategic locations in mines and mills have all combined to reduce radiation exposures in uranium mining and milling. Some current radiation doses to Cameco mine personnel are shown in Table 1. The anticipated doses from the new developments are similar and all are lower than doses experienced in the past in mining the lower-grade deposits at Elliot Lake and Uranium City.

Tailings management has evolved over the past twenty years from the use of natural water bodies, through purpose-built surface facilities, to the current approach of placing tailings in mined-out open pits. Eagle Point, Key Lake and McClean Lake all use variations of this technology, the 'pervious surround design' [5]. By means of a drainage drift and pumping system, water is pumped from the bottom of the pit. This drains and consolidates tailings placed in the pit and creates a cone of depression in the groundwater system which prevents loss of contaminants from the pit. Water pumped from the pit is recycled to the mill or treated and released. Decommissioning of the system requires that the tailings have a substantially lower permeability than the surroundings. This may be accomplished by selection of a location with favourable hydrogeology or by placement of a highly permeable crushed rock and sand liner in the pit before tailings are deposited. The result, after the pumps are shutdown, is a relatively impermeable mass of tailings surrounded by highly permeable material, the 'pervious surround'. The groundwater takes the path of least resistance around, rather than through, the tailings. The only loss of contaminants to groundwater is via molecular diffusion. Twelve years of operation at Rabbit Lake have yielded results better than the modelling predictions [5]. This augurs well for decommissioning, which will commence in another five years.

TABLE 1: TYPICAL RADIATION DOSES IN URANIUM OPERATIONS

OPERATION	INTERNAL (mSv)		Whole Body (mSv)		SKIN (mSv)		EFFECTIVE (mSv)	
	Average	Maximum	Average	Maximum	Average	Maximum	Average	Maximum
Underground Mine	3.4	11	1.7	8.4	NM	NM	5.1	17
Open Pit Mine	0.8	1.7	0.5	4.4	NM	NM	1.4	4.8
Mill	3.3	10	0.7	4.4	NM	NM	4.0	12
Refinery	0.9	14	1.5	11.6	5.1	45.9	2.4	25
UO_2 Plant	1.4	14	1.3	4.4	3.9	21.0	2.7	16
UF_6 Plant	0.5	14	2.1	11.8	10.5	64.9	2.6	17
Fuel Fabrication	0.9	8.6	1.9	12.1	6.8	68	2.8	20

Notes: Internal dose is radon progeny converted at 5 mSv/WLM plus ore dust or uranium dust exposure.
NM = Not Measured. Skin dose is not limiting in mining operations and a more robust badge is used, which reduces lost data, but precludes skin dosimetry.

In open-pit mining, elaborate pumping systems are used to collect water before it gets into the pit, so that it can be released to the environment without treatment. Pit water and underground mine water are contaminated with high levels of suspended solids, some Ra-226 and, depending upon the particular ore body, arsenic and nickel. This water is usually diverted to the mill for process use or for treatment before release along with the aqueous waste from the milling process. Water may be released batch-wise with analysis of each pond before release, or it may be released and sampled continuously. The licences for all operating mines specify discharge concentration limits and discharges from operating mines are well below those limits. In particular, concentrations of Ra-226 in discharge waters are consistently below the Canadian drinking water objective of 0.6 Bq/litre and uranium concentrations meet the drinking water objective of 100 µg/litre within the mixing zone at the discharge point [6].

Radon from mine exhausts represents the largest single airborne radionuclide discharge, but environmental measurements indicate that concentrations are not distinguishable from natural background at distances of a few kilometres from the source (in agreement with modelling predictions) and well within the normal temporal variations in background [7]. In the McArthur River environmental impact statement, the cumulative dose to members of the nearest community from all the mine developments in northern Saskatchewan was calculated to be about 29 mSv/a, about 1% of the natural background, of about 3000 mSv/a [8].

2.3. Refining, conversion and fuel fabrication

At the Blind River Refinery, the uranium concentrate is dissolved in nitric acid, purified by solvent extraction and converted to UO_3. The principle waste from refining, the raffinate from solvent extraction, is recycled for recovery of the uranium. Historically the raffinate was shipped to the Elliot Lake uranium mills in Ontario, but with the closure of the Elliot Lake operations, Blind River converted its process to produce a dry product, containing 5% to 7% uranium for safer handling in transport to Saskatchewan uranium mills.

At Port Hope, about 80% of the UO_3 is reduced to UO_2, reacted with hydrofluoric acid to produce UF_4, which is reacted with fluorine to produce UF_6 for shipment to enrichment plants outside Canada and entry into the light water fuel cycle. The remaining UO_3 is converted to ceramic grade UO_2 for use in the CANDU (NU) fuel cycle. As in the refinery, extensive internal recycle takes place. Uranium-bearing material which is unsuitable for internal recycle is converted to a dry concentrate suitable for recycle to a uranium mill.

The Zircatec Precision Industries Inc. and General Electric Canada CANDU fuel fabrication plants make sintered pellets from the UO_2 and load these into fuel pencils and assemble the pencils into CANDU fuel bundles. Most uranium wastes from the fuel fabrication plants are recycled to the Blind River Refinery. A small volume of contaminated material unsuitable for recycle is currently stored.

Because most of the radium has been separated from the uranium at the mill, radon progeny are not a problem in the refining and later stages. The potential for external exposures can be significant in some process areas, particularly where uranium is separated from its short-lived progeny (Th-234 and Pa-234), in the Blind River raffinate process and in the Port Hope UF_6 process. Control of appendage doses is also important in fuel fabrication, where there is a lot of manual handling of pellets and fuel elements. There is also potential for uranium dust exposure in several places in these operations. Typical radiation doses at Cameco and Zircatec facilities are shown in Table 1.

Emissions to the environment are small at all of these operations. The most significant emission at the refinery is uranium in exhaust air, which averages about 0.14% of the Derived Release Limit. Because the Port Hope conversion facilities are located within an urban area, fence-line gamma radiation fields as well as uranium discharges to atmosphere are closely monitored and form part of the licence conditions. The combined dose from all sources at the nearest residence, located within 400 m

of the plant is calculated to be about 0.25 mSv/a. Emissions from Canadian fuel fabrication plants are at least an order of magnitude smaller than from the refinery and conversion plants.

2.4. Environmental restoration of old uranium mining/milling sites

As described in the preceding sections, uranium tailings and other uranium mining wastes are well managed, in a range of systems designed to protect the environment and minimize impacts, both during production and after decommissioning. This was not always the case, and remedial action programs have been implemented, or are being planned, in a number of countries where tailing sites were abandoned, or where the simple impoundments used many years ago are inadequate for the longer term [9]. In the U.S.A., the DOE is nearing completion of the Uranium Mill Tailings Remedial Action (UMTRA) program at 26 sites dating back to the 1950s and 1960s. In Germany, a major government program involving both conventional mills and tailings sites, and in situ leaching operations, is under way at sites operated by the company WISMUT in the former German Democratic Republic. Planning is under way for sites in a number of Central and Eastern European countries, with technical assistance from the IAEA [10].

Examples can also readily be found of sites where production which began many years ago has ceased quite recently, and where decommissioning plans are being developed and implemented by the mining companies. In Canada, for example, environmental assessment hearings have just been completed for the closure of sites in the Elliot Lake area of Ontario containing about one hundred million tons of tailings [11]. Other projects can be found in a number of current or former uranium producing countries, for example Australia, Czech Republic, France, Spain and the U.S.A.

3.   NUCLEAR POWER PLANTS

3.1.   Occupational dose

Occupational doses at nuclear power plants have decreased over the past thirty years, while the amount of electricity produced from nuclear energy has increased [12]. Most, up to 90%, of the worker doses are accumulated during periods of plant shutdown. In recent years, outages have normally been planned shutdowns to perform maintenance or to refuel, in the case of LWRs. Extended maintenance outages have been less frequent than during the 1970's, so capacity factors—the fraction of the time that the plant is available to produce electricity—have risen, contributing to the increased output of nuclear energy.

Shutdown doses are dominated by exposure to activated corrosion products. This material originates in the high-flux region of the reactor core or is transported to that region during plant operation. Any material activated in the core can be transported by the coolant to the wetted surfaces of the out-of-core components. The growth of oxide layers on these surfaces incorporates activity. Hence, subsequent maintenance work is in a radiation field from deposited corrosion-product activity. Historically, much of the worker dose has been from one radionuclide, Co-60. This radionuclide is formed from elemental cobalt that is normally present as impurities in the steels used to construct the coolant system and from the cobalt present as an alloying component of specialty materials such as Stellites.

Reductions in worker exposures have been driven by the ALARA principle. From the evidence of the operating plants, the greatest reductions in worker doses appear to have come from changes in material. Current designs of reactors emphasize the following:

- layout of plant equipment to provide good access to equipment;
- optimization of coolant chemistry to minimize corrosion;
- careful specification of materials to eliminate or reduce cobalt content;

- automation of routine tasks and the use of robotics; and
- decontamination, as an integral step in maintenance, e.g., in the replacement of steam generators. (The collective dose from steam generator replacements have declined monotonically over the past 15 years to 0.5 person Sv per steam generator, a total reduction of about a factor of 10 [12].)

Other factors play a role, for example, improving the reliability of equipment, training and job planning, including as mentioned above, decontamination. These factors have been used effectively in older plants to control and reduce worker exposures.

3.2. Dose to the public

As the total energy produced by nuclear power has increased, collective doses to the population have also increased, but that dose has remained a negligible fraction of the dose from natural background [13]. Based on the dose-conversion factors used in the UNSCEAR model for population dose [13] the local-regional dose is expected to be most sensitive to airborne releases of particulates, C-14 and radioiodine. The integral dose to the local-regional population up to 1989, however, shows that the actual dose has been dominated by C-14, noble gas and airborne-tritium releases. This illustrates the effective measures used by nuclear-power plants to control the most dose-sensitive pathways. In addition, relative doses from the three primary contributors to the calculated dose have been declining [13].

3.3. Future trends

Extrapolating past experience into the future leads to the following conclusions:

1. Based on environmental impact, there is no economic reason for nuclear reactors to reduce emissions; doses from the existing reactors are negligible fractions of those from natural sources.

2. Despite this, emissions are expected to continue to decline as reactor vendors evolve their products and reactor operators optimize their procedures.

3. Occupational doses from routine operations and maintenance are likely to continue to decline, reflecting improvements in equipment and procedures, but the extent will necessarily involve a trade-off of costs, both capital and operating, and benefits.

4. The general public seems not to appreciate the low environmental impact of nuclear power plants. The future of nuclear energy will depend on providing reassurance to the public and decision-makers. International co-operation and open, honest, consistent, and clear communication with all stakeholders are absolutely essential to achieving this end.

4. REPROCESSING FACILITIES

4.1. Occupational exposures

Both the United Kingdom and France reprocess used fuel on a commercial scale, at Sellafield in the U.K. and at La Hague in France. As with doses to workers at nuclear power plants, occupational exposures at these reprocessing facilities have shown a significant decline with time. For example, at Sellafield, average doses, the total collective dose and the number of staff receiving doses greater than 15 mSv in a given year have all decreased by close to an order of magnitude over the past 15 years or so [14]. The average occupational exposure at Sellafield for all activities, including decommissioning, is now less than 2 mSv [15] per year comparable to the natural

background radiation in the area, while at La Hague, the average annual exposure in 1994 was 0.26 mSv [16]. From 1987 to 1993, total exposures at La Hague decreased from 5 person Sv to less than 2 person Sv, while the amount of fuel reprocessed at the plant more than doubled [16].

Dose reductions are attributable to a number of factors including the following:

- the introduction of new facilities designed to minimize radiation fields;
- improvements in shielding, equipment, ventilation, and segregation of work areas; and
- a focus on dose reduction.

The latter involves the promotion of a safety culture with buy-in from all—staff, managers and operators alike; improvements in dosimetry and dose control such as the use of electronic dosimeters; the use of static and personal air samplers to monitor and then reduce internal exposures; dose tracking and job analyses to facilitate work planning and procedure development; improvements in housekeeping; and enhanced training, including the use of mock ups and computer simulations. Many of these techniques have also been used in power plants, particularly for dose reductions during maintenance.

As with power plants, major maintenance and refurbishment work has been carried out with modest radiological exposures. For example, the 13 Mg dissolver unit in the magnox reprocessing system at Sellafield was replaced manually at a collective dose of about 12 person Sv, compared with an initial estimate of 26 person Sv [17]. A major contributor to this success was an effective dose management system that linked dose control with job planning and work control and which included feedback of dosimetry results to modify future work practices.

4.2. Releases and public doses

As with occupational exposures, releases from reprocessing facilities have also shown significant reductions. In the vicinity of Sellafield, environmental impacts to the public are today about a factor of ten less than 15 years ago and are at a small fraction of dose rates from natural background radiation [18, 19]. Airborne and liquid discharges have been progressively reduced with the introduction of treatment facilities to process waste streams before discharge. Treatment facilities at Sellafield include the Site Ion Exchange Effluent Plant and the Enhanced Actinide Removal Plant [19, 20]. The latter began operation in 1994 March and has reduced discharges of plutonium, americium, and a number of beta-emitters, significantly. In recent years, beta discharges have shown modest increases since the treatment of historic stored liquid wastes has begun. Similarly at La Hague, releases have decreased significantly in the last decade, while plant production has increased. The total radiological impact of the La Hague plant, including both liquid and gaseous releases has been estimated at less than 10 μSv per year [16].

5. DECOMMISSIONING AND WASTE DISPOSAL

A considerable body of experience has been developed with the decommissioning of nuclear facilities as reported in reference 21. In decommissioning nuclear facilities, dose assessments and control of exposures and of releases are integral to work planning and decision-making. The assessment of radioactive inventories is seen as the essential first step in defining the requirements of a decommissioning project. Such inventories are required for planning, for safety assessments, and for waste characterization and disposal, including release and recycle.

Doses can be controlled using a variety of techniques including the following: decontamination, the deployment of robotic systems, the use of shielding, careful work planning, training, including the use of mockups and rehearsal facilities, the use of electronic (real time) dosimeters, the use of feedback of operational experience and attention to detail. Dose monitoring

and control are important elements since many aspects of a given project present new and/or unique situations. See, for example, references 22 to 24. The actual occupational doses received are, in general, lower than those estimated when assessing the work.

In decommissioning, criteria are applied for the unconditional release of materials or for their conditional release, e.g., for recycle and reuse [25]. Such releases are governed, today, by case-specific criteria which vary from country to country and project to project. Progress is being made on developing international guidance regarding release and recycle and reuse of material from nuclear facilities. See for example references 26 to 31. While the proposals of the IAEA and the European Commission are useful, they do not address completely the issue of conditional release or they are restricted in their application. Further, while recycle and reuse options present a cost-effective method of dealing with waste arising from decommissioning, their deployment may be limited by the need to restrict doses to very low levels. For example, the IAEA derivation of unconditional clearance levels is based on restricting individual doses received by the public from a given project to 10 μSv per year [26, 27, 29].

Regardless of the evolution of release criteria, there will, nonetheless, be a need to manage radioactive wastes that arise from decommissioning and from operational nuclear facilities. As with other wastes that arise from all human activities, there are two main options for managing radioactive waste. The first is to contain and isolate the waste from the environment for as long as is necessary. The second option is to disperse material in the environment at levels which do not produce an unacceptable radiological risk. In the case of dilution and dispersion, the quantities released to the environment must be controlled, to ensure that human health and the natural environment are protected and as discussed in previous sections, releases from nuclear facilities and the consequential exposures have decreased significantly in recent years and, today, can be regarded as inconsequential.

While dilution and dispersal have been used to a limited extent, the majority of radioactive waste is contained and isolated. Many years of experience have been accumulated with storage systems to contain and isolate such waste. Such systems have clearly demonstrated that they meet the objectives of protecting public and occupational health and the environment. Long-term storage is a suitable waste disposal strategy for radioactive waste having a relatively short half-life, e.g., spent Co-60 sources. After a suitable period of storage, (up to a few hundred years) the hazard from such waste will decay to a level at which there is no residual risk to human health or the environment. Such long-term storage systems, when appropriately designed and licensed, can be used for final disposal of radioactive waste containing predominately short-lived radionuclides. Once the waste has been emplaced, there is no intent to retrieve the waste for further processing. Near-surface and shallow rock disposal systems for short-lived waste are in operation in a number of countries, e.g., Finland, France, Japan, Spain, Sweden and the U.S.A.

The releases from these facilities are today negligible. For example no liquids are released at all from the Spanish low-level waste disposal facility at El Cabril, the waste water being used on-site in fabricating grouts and cements used to encapsulate the waste. Airborne releases are limited by regulation to contribute a maximum dose to a member of the critical group of at most 0.01 mSv per year, well below the ICRP recommended dose limit for a member of the public of 1 mSv per year. Actual releases in 1995 were less than 1% of this limit [32]. At the Drigg site adjacent to the BNFL reprocessing complex at Sellafield, the amounts of radioactivity discharged have decreased substantially over the past several years so that today calculated doses to members of the hypothetical critical group are extremely low, less than 0.01 μSv from liquid discharges and several μSv per year from airborne discharges [19]. Similar experiences have been obtained at other low-level waste disposal facilities. Worker exposures are also correspondingly low.

Some radioactive materials, particularly used nuclear fuel and the long-lived waste that occurs from reprocessing used fuel, have a much longer half-life and present a hazard for many

thousands of years. The long-term management of such material presents special considerations. Nuclear fuel waste is presently stored, either in wet storage (water-filled pools) or in dry storage systems (concrete or metal structures). While supporting research and development (see for example, references 33 and 34) indicates that such storage practices can safely continue for many decades to come, there is a recognition that storage must be considered an interim measure for long-lived waste.

Based on the need to ensure long-term safety and an ethical concern for future generations, many countries are developing technology to dispose of long-lived radioactive waste, particularly nuclear fuel waste. The disposal concepts being developed internationally for deep geological disposal are based on a combination of engineered barriers and the natural barrier provided by the host geological medium. The key engineered barriers include a stable waste form, either used fuel or stabilized waste from reprocessing used fuel; long-lived containers into which the waste form is packed; clay-based buffer materials that separate the containers from the host geological structure and control the movement of water to, and corrosion products away from, the containers; and seals and backfill materials to close the various openings, tunnels, shafts and boreholes. There is international consensus among waste management experts that this approach can best achieve the goal of safely managing nuclear fuel waste in the long term [35]. There is no essential difference in disposal requirements nor in the designs of disposal systems between the direct disposal of used fuel and the disposal of solidified high level waste from reprocessing. Both wastes need to be disposed and both waste forms are suitable for disposal [36, 37].

Assessments of repository performance have been carried out (e.g., Canada [38, 39], Sweden [40, 41], Switzerland [42] and Japan [43]), as well as reviews of the concept of deep geological disposal by international organizations, and the approach is considered to be feasible in providing a passively safe option for disposal that will not harm either humans or the natural environment. Currently, the international perspective is that disposal facilities for long-lived waste will not be operational before about 2010-2020. National efforts, for the most part, are concentrated on research and development activities to evaluate the safety and feasibility of various alternatives, the selection of suitable disposal sites and optimization studies covering safety, environmental, industrial and economical issues.

6.   CONCLUSIONS

Based on the foregoing discussion it is clear that releases and occupational exposures from modern nuclear facilities of all types contribute negligibly to the radiation environment to which all biota are exposed. Nonetheless, releases, and to a lessor extent worker exposures and safety, are the subject of intense scrutiny by environmental activists and the media.

As evidenced by the response of the industry, in the past, there was room for significant improvements. But it is not clear what the reaction of the industry will be or, indeed, should be in the future. The concept of zero release, which represents the aspirations of the environmentalist lobby, cannot be realized in practice. Rather, the approach adopted by the industry and its regulators has been to follow the advice of the ICRP and to keep doses as low as reasonably achievable, social and economic factors taken into account. Based on the level of performance that is being achieved in modern nuclear facilities, emissions and occupational exposures are, in the opinion of the authors, already as low as reasonably achievable. Should not, therefore, the industry and organizations such as the ICRP defend this performance as de minimis for all practical purposes? The industry would then be better able to focus on problems that will lead to greater benefits for the investment made rather than devoting large sums seeking to improve still further the performance of modern facilities.

The general public seems not to appreciate the low environmental impact of nuclear activities. The future of nuclear power—and of other applications of nuclear technology,

applications in medicine, in agriculture and in industry—will depend on reassuring the public and decision-makers that the industry is safe. International co-operation and open, honest, consistent, and clear communication with all stakeholders are absolutely essential to providing this assurance and, hence, the survival and growth of nuclear technology. Today, any industry must meet the objective of sustainable development if it is to survive. For the nuclear industry this means controlling occupational exposures and the releases of radioactivity into the environment. These requirements have been of fundamental importance to the industry since its inception. The industry has much to be proud of, but as we look to the future we need to avoid complacency and to continue to maintain the current high level of performance.

ACKNOWLEDGEMENTS

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TRANSMUTATION OF RADIOACTIVE WASTE: EFFECT ON THE NUCLEAR FUEL CYCLE

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Abstract

A committee of the National Research Council reviewed three concepts for transmuting radionuclides recovered from the chemical reprocessing of commercial light-water-reactor (LWR) fuel: LWR transmutation reactors fueled with recycled actinides, advanced liquid-metal reactors (ALMRs), and accelerator-driven subcritical reactors for transmutation of waste (ATW). The concepts were evaluated in terms of: (1) the extent to which waste disposal would benefit from transmutation, (2) time required to reduce the total inventory of radionuclides in the waste and fuel cycle, (3) the complexity of the overall transmutation system, (4) the extent of new development required, and (5) institutional and economic problems of operating such systems. Transmutation could affect geologic disposal of waste by reducing the inventory of transuranics (TRUs), fission products, and other radionuclides in the waste. Reducing the inventory of transuranics does not necessarily affect radiation doses to people who use contaminated ground water if the dissolution rate of transuranics in waste is controlled by elemental solubilities. However, reducing inventories of Am and Pu would decrease potential hazards from human intrusion. The likelihood for underground nuclear criticality would also be reduced. The long-lived fission products Tc-99, I-129, Cs-135 and others typically contribute most to the long-term radiation doses to future populations who use contaminated water from the repository. Their transmutation requires thermal or epithermal neutrons, readily available in LWR and ATW transmutors. ALMR and LWR transmutors would require several hundred years to reduce the total transuranic inventory by even a factor of 10 at constant electric power, and thousands of years for a hundred-fold reduction. For the same electrical power, the ATW could reduce total transuranic inventory about tenfold more rapidly, because of its very high thermal-neutron flux. However, extremely low process losses would be required for the ATW.

1. TRANSMUTATION CONCEPTS

1.1. Concepts reviewed

The National Research Council committee reviewed three principal concepts for transmuting radionuclides recovered from spent fuel discharged from commercial light-water reactors (LWRs). The transmutation concepts were proposed in the U.S. for the purpose of simplifying the disposal of high-level waste. The three principal concepts were LWR reactors to transmute transuranics and fission products; advanced liquid-metal fast-spectrum reactors (ALMRs) proposed by the U.S. Department of Energy (DOE) to transmute transuranics; and fluid-fuel accelerator-driven subcritical reactors (ATWs) proposed by the Los Alamos National Laboratory (LANL) to transmute transuranics and fission products. Details are given in the committee's report [1]. Both DOE and LANL expected that their proposed concepts would significantly reduce the time required to isolate the remaining high-level waste from the environment. Each concept was accompanied by proposed new chemical processing for high-yield recovery and recycle of radionuclides to be transmuted, including on-line reprocessing of the ATW fluid fuels.

Each of these three transmutation concepts has been proposed as an alternative means of generating commercial electrical energy while reducing the amount of radionuclides that go to waste disposal.

1.2. Time to reduce the Transuranic (TRU) inventory

ALMR proponents speak of reducing the transuranic content of wastes by factors of 1,000 or greater, compared to the transuranics in unreprocessed spent fuel of the same electrical energy

185

generation. ATW designers propose an even larger reduction in inventories of transuranics and key fission products, so that the remaining wastes would need to be isolated for "no more than a human lifetime."

In each of the concepts only a small fraction of the radionuclides charged to the transmutor is actually consumed during an irradiation cycle. Thus, the radionuclides recovered from transmutor discharge fuel must be recovered and recycled many times. Only a partial net reduction occurs during each reactor lifetime, the untransmuted radionuclides being passed to the next generation of reactors for further reduction. This is particularly true for the LWR and ALMR transmutors, although more rapid transmutation could theoretically be accomplished in the high-flux fluid-fuel ATWs.

During the long time for transmutation much of the radionuclide inventory will still appear in the reactor and fuel cycle. There can be no assurance that nuclear energy generation by reactors, including transmutor reactors, would continue for such long times or that similar transmutor reactors would be chosen to continue transmuting inventory remaining from previous transmutors. Therefore, the inventory of untransmuted radioactivity in the reactor and fuel cycle must also be considered as a potential waste.

The committee adopted as a performance index the ratio of accumulated radionuclide inventory in a reference LWR fuel cycle, operating without recycle and transmutation, to the inventory in a transmutation fuel cycle of the same electrical power. This ratio increases with time. Transmutation of total transuranics was emphasized in the transmutor concepts, so calculations were made of the transuranic ratio, a measure of the net inventory reduction of transuranics relative to the accumulated transuranic inventory produced by the reference once-through LWR. For an ALMR with a conversion ratio of 0.65 (a conversion ratio sufficiently high to preserve passive safety features and low enough to reduce the rate of production of new transuranics), and for 0.001 percent of the processed TRU appearing in the waste, several hundred years would be required to reduce the total transuranic inventory by even a factor of 10 at constant power. Thousands of years would be required for a hundred-fold reduction. Neither would meet the inventory reduction goal claimed for ALMR transmutation. The asymptotic transmutation ratio reached at longer times is less than the reciprocal of the fraction of transuranics processed that is lost to waste, because on average transuranics must be recycled many times through the reactor and reprocessing.

A LWR transmutor, with high-recovery reprocessing and transuranic recycle of mixed-oxide (MOx) fuel, would have a transmutation time constant similar to that predicted for the ALMR. However, transmutation with the thermal neutrons of an LWR would produce greater quantities of higher-mass transuranics than the ALMR and may require U-235 addition to achieve criticality at steady-state recycle. LWR transmutors could also transmute the long-lived Tc-99 and I-129 fission products that are predicted to be significant contributors to long-term radiation doses from geologic disposal.

The nonaqueous fluid-fuel ATWs would achieve much higher transuranic ratios in a given time, because of the extremely high thermal-neutron flux ($2 \times 10^{15}/cm^2sec$) claimed for the concept. Only about 7 years of steady-power operation would be required for a transuranic ratio of 10 and 40 years for a ratio of 100. The troublesome long-lived fission products Tc-99, I-129, and Cs-135 would also be transmuted. However, far greater transmutation ratios and longer times would be required to achieve the LANL goals for the ATW. The calculated transmutation performance must be balanced against the formidable problems of operating at the high required power density, as well as the practicality of the very complex on-line reprocessing system designed to achieve extremely low process-losses.

If nuclear power is assumed to phase out more rapidly, instead of operating at constant power for centuries assumed above, transmutors could be reduced in number and in total power as the total transuranic inventory now expected from the current U.S. LWRs is consumed. Such a declining-power scenario would achieve more rapid reduction in the radionuclide inventory, but the times required for the significant reductions by LWR and ALMR transmutors would remain long. For example, ALMR transmutors could achieve a TRU inventory ratio of 11 in 100 years, as compared to about 7 for constant

power. Two centuries would be required to obtain a TRU ratio of 100, still tenfold lower than that desired by the ALMR designers.

1.3. State of technology and safety of LWR transmutor systems

The LWR is the most mature concept for transmuting transuranics and fission products. It relies on well-established technology for low-enriched uranium-dioxide fuel. Safety problems associated with recycle of transuranic fuel would have to be resolved. These include control-rod effectiveness and reactivity control, as well as safety of a new system for high-recovery reprocessing and fabrication of transuranics of much higher alpha and neutron activity than would exist in the ALMR transmutation fuel cycle. Plutonium recovered from first-cycle UO_2 is being recycled once as LWR MOx fuel in France and other countries. Far more technical problems are expected for multiple recycle of recovered transuranics as LWR MOx fuel. Multiple recycle would be necessary to destroy appreciable quantities of transuranics that would otherwise appear in radioactive waste.

There are no U.S. facilities for fabricating commercial mixed-oxide fuel or for reprocessing uranium fuel discharged from LWRs. Separations and target materials for fission-product transmutation would need development. New high-recovery processes would have to be developed, as well as new systems for reprocessing and fabricating multiple recycled transuranics in MOx fuel. These fuel-cycle facilities would require major technological development. Because of the estimated high cost of fuel reprocessing and fabricating recycle MOx fuel in new U.S. facilities, there are no clear financial incentives for commercial development of such facilities in the U.S., now or probably for many decades in the future.

1.4. State of technology and safety of ALMR transmutor systems

The ALMR transmutor would rely heavily on fast-breeder liquid-metal technology already developed in the U.S. and abroad. Designs with conversion ratios well below 0.65 would accelerate transmutation but would introduce new safety concerns associated with positive sodium-void coefficients. New safety issues will arise from reactor fuel containing Np-237 and other multiple recycled transuranics and fission products.

Existing PUREX separation technology, together with TRUEX for higher recovery, could be used to recover transuranics from LWR discharge fuel for transmutation in ALMRs. However, DOE's proposed new pyrometallurgical separation for uranium-dioxide fuel would require major development. Whether aqueous or pyrometallurgical processing is used, the required throughput of 2,700 Mg/yr of LWR spent fuel would far exceed the capacity of any commercial plant built in the U.S. or abroad. The pilot plant demonstrations of pyrometallurgical reprocessing EBR-II fuel would not be sufficient to establish the technology and to resolve licensing issues of reprocessing LWR fuel and reprocessing and fabricating multiply recycled transuranic fuel from an ALMR transmutor. Remote maintenance and process control are key problems that must be resolved in designing a licensed industrial-scale facility. Extensive tests to qualify the new waste forms for geologic disposal would be necessary.

1.5. State of technology and safety of ATW transmutor systems

The ATW is a subcritical assembly of $k_{eff} = 0.95$, driven by a neutron-producing high-current accelerator. Most of the transmutations occur from reactor-produced neutrons. LANL states that the main benefit from the accelerator would be to avoid safety issues of critical reactors. No control absorbers are to be provided. However, a high-flux fluid-fuel reactor such as the ATW is likely to be subject to greater reactivity swings than can be controlled by an accelerator designed for $k_{eff} = 0.95$. Also, because most of the energy produced is from fission, the ATW would be subject to problems of emergency removal of fission-product decay heat, made severe by the extremely high power density.

187

In the event of a loss of coolant flow, the ATW fluid fuel must be promptly cooled to prevent overheating and to prevent volatilization of many of the radioactive species that are already in a mobile form in the fluid fuel. The ATW design has not confronted the pipe-break criterion adopted for reactor licensing. The molten-salt ATW would introduce additional safety problems such as containment of the molten-salt fuel, possible xenon instability at high thermal flux, xenon interaction with graphite moderator, and shutdown by Sm-149 following power fluctuations. Fluid-fuel boundary-layer heating, a crucial problem in earlier fluid-fuel reactors, will be more severe at the high thermal flux. Also, because of the high thermal flux, the production of americium and curium will be far greater than in the ALMR and LWR transmutors. The high alpha and neutron activities will add to the large radioactivities of fission products in the fluid fuel and the integrated reprocessing systems. Loss of integrity of the spallation target and its cooling system, especially in the high-flux region, could be detrimental to reactor safety. The safety problems of the ATW concepts are expected to be far more severe than for the ALMR and LWR transmutors.

All reprocessing operations proposed for the ATW are new and unproven. Instead of relying on aqueous reprocessing to recover transmutable transuranics and fission products from LWR spent fuel, LANL proposes to develop a new nonaqueous fluoride volatility process with extremely low process losses to waste. Several separate nonaqueous on-line chemical separations are also planned: (1) continuous reprocessing of spallation targets to recycle radioactive spallation products for transmutation, (2) cascades of ultracentrifuges, operating on molecular-weight differences of solutes, to separate transuranics and fission products from the molten fluoride salt and from each other, and (3) isotopic separation of Cs-135, in the presence of highly radioactive Cs-137, to form pure Cs-135 targets for transmutation. The required process losses per cycle through the on-line separation units are extremely low, less than 2×10^{-4} per cycle for plutonium and neptunium and 3×10^{6} for americium and curium. Even the basic technical feasibility of such processing in the intense radiation fields is subject to question.

LANL has not sufficiently addressed the issues of whether greater reliability and safety, as well as more economical operation, could be obtained with a critical reactor of similar design but not incorporating the neutron-producing accelerator. Make-up U-235 could be added if additional neutrons are needed for transmutation.

2.   SEPARATIONS REQUIRED FOR TRANSMUTATION

For separation and transmutation of actinides, some form of aqueous separations involving a combination of PUREX and TRUEX solvent extraction processes could be used with any of the transmutation concepts.   Although PUREX usually produces separated streams of uranium and plutonium, as well as high-level waste containing fission products and transplutonics, a PUREX modification is available to produce separated neptunium as well. However, the PUREX recovery fractions are not large enough to produce the degree of transuranic recovery desired by transmutation proponents. TRUEX would be added for high recovery and recycle of transuranics. TRUEX utilizes organophosphates such as carbamoylmethylphosphineoxide (CMPO). TRUEX may also be adaptable to extracting and separating the heptavalent technetium fission product. Additional research and development would be required before full plant-scale use of the TRUEX technology. The high-level-waste form for geologic disposal would be borosilicate glass. Additional TRU waste and low-level waste would be generated.

Transmutation of long-lived fission products would require development of additional separations to be added to PUREX. TRUEX using CMPO extractant could removed technetium from acidic fuel solution. Processes are already available to separate carbon-14, radioiodine, and cesium, but improvements in recovery efficiency may be needed.

The Argonne National Laboratory (ANL) advocates the Integral Fast Reactor (IFR) fuel separation process, both for processing ALMR metallic fuel for recycle and for processing LWR spent fuel to recover and recycle transuranics for transmutation in ALMRs. ANL believes that such reprocessing facilities of small capacity and integral to individual ALMRs could be economical. The IFR process is based on the selective electrorefining of uranium, plutonium, and other actinides from a molten cadmium solvent (the anode), into which they have been dissolved by anodic dissolution of spent IFR or LWR fuel. The IFR process is designed to separate the transuranic actinides as a group and does not produce an essentially pure plutonium stream. Rare earth fission products are recycled along with the transuranics. Other fission products collect at the anode. New waste forms are generated and must be extensively tested to qualify for geologic dispoal. There are many sources of secondary waste that must be dealt with.

The IFR reprocessing system would consist of a large number of compact, criticality-limited electrorefiners operating in parallel to obtain suitable throughput. Each must be operated batchwise, as contrasted to the continuous operation of the PUREX system. Process control and maintenance are key issues. The IFR reprocessing system would need considerable development and testing before it could be considered suitable for commercial operation. Application of the pyrometallurgical process to LWR spent fuel has been proposed but is far from pilot-scale demonstration. The practicability of integrated reprocessing at commercial nuclear power plants is questionable.

The Los Alamos National Laboratory proposed two entirely different fluid-fuel ATW reactors to transmute fission products and transuranics, one based on a high-pressure slurry of transuranics in heavy water and another based on a fused-salt solution of transuranics and fission products. Los Alamos has since focused on the fused-salt system described herein. The molten salt consists of Li^7-Bi-Th fluorides, with a melting point above 500°C, containing transuranics and fission products. The molten salt circulates through heat exchangers to boil water and generate electrical power. The principal design feature of the ATW is operation at very high neutron flux to reduce the time required for a given percentage conversion of transmutable species. This requires high specific thermal power (thermal power from fission per unit mass of fissile species in the entire transmutation system[1]). To minimize the fissile inventory that would otherwise exist in a separate reprocessing system, the ATW design proposes on-line reprocessing.

The ATW on-line separation system must be resistant to the enormous alpha and neutron activities, exacerbated because the transuranics in the circulating fuel will be mainly americium, curium, and even higher-mass transplutonic species. The variety of nonaqueous separations, including fluoride volatility and molten salt processes, now under study, pose challenging problems of corrosion and containment. The required separation factors are extremely high[2], far beyond any yet demonstrated. LANL proposes to develop high-temperature ultracentrifuges that operate on molecular-weight differences of solutes in the molten salt. To transmute Cs-135 it will be necessary to separate Cs-135 from the other cesium isotopes formed in fission, to avoid further generation of Cs-135 by neutron capture in stable cesium. Separating these isotopes in the presence of the enormously high activity of Cs-137 would be a formidable problem, never before encountered in isotope separation. The ATW separations concepts are at such a preliminary stage of study that any judgment on their technical viability is premature.

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[1]   The ATW is designed to be accelerator driven with k_{eff} = 0.95. Most of the neutrons for transmutation come from fission of transuranics. High specific power based on fissile material ensures high neutron flux for transmutation, as it does in critical systems.

[2]   Maximum allowable process losses, to achieve the design goals, are 0.02 percent for plutonium and neptunium and 0.0003 percent for americium and curium, for both on-line separations of the fused-salt mixture as well as for the separate reprocessing of LWR spent fuel.

3. IMPACTS ON WASTE DISPOSAL

3.1. The need for an adequate measure of performance

All of the proposed systems for transmuting radionuclides present in LWR spent fuel have the potential to affect the design and long-term performance of disposal systems for spent fuel and other radioactive waste. The waste going to geologic repositories would contain reduced quantities of several radionuclides and would generate less thermal power. It would be in forms different from spent fuel, with the potential of designing waste forms tailored more to the demands for stability and slow release in a geological environment. Even reprocessing without recycle and transmutation could accomplish the latter. The claims of possible benefits to geological disposal have ranged from eliminating the need for a U.S. geological repository to providing a sounder technical basis for licensing. Another claimed benefit is that reducing the decay heat rate of the waste would permit a given repository site to store waste from a greater amount of electrical energy generation, thereby eliminating or postponing the need for a second repository.

Unfortunately, the many claims of benefits to waste disposal have not been scientifically based. Claims of reduced hazard from radioactivity have relied on toxicity calculations that compare the toxicity of spent fuel to that of uranium ore. Toxicity at any future time is calculated from the inventory of radionuclides weighted by the biological effectiveness of each radionuclide if assimilated into the human body. It does not indicate even the relative hazard, because it takes no account of the probability that a radionuclide in a disposal system will eventually escape and reach the environment. Also, comparison with uranium ore is not a valid measure to determine what might be an acceptable reduction of the amounts of radionuclides in waste [2].

A valid performance assessment of a radioactive waste repository must evaluate possible future conditions and events that might allow radioactivity to be released to the environment and cause radiation doses to future populations. Two general areas are typically addressed: (1) transport of radioactivity from the waste solid, through geologic media, into the human environment, and (2) disruptive events and inadvertent human intrusion that could cause a portion of the repository contents to be directly transported to the surface or injected into flowing ground water.

3.2. Radiation doses from hydrogeologic transport

Calculations made to date show that doses to future individuals may result mainly from long-lived radionuclides. The most important in ground-water pathways are typically the long-lived fission products Tc-99, Cs-135, and I-129. None of these are important contributors to waste toxicity. For a repository in unsaturated rock, such as the proposed Yucca Mountain site in the U.S., Np-237 may also contribute importantly to long-term doses from hydrogeologic transport [3]. Pa-231 and Ra-226, decay-daughters of the long-lived U-235 and U-238 in waste, can also be important long-term contributors. To the extent that long-term doses from these species are threats to public health, reprocessing spent fuel would create the opportunity to sequester each of these species (or their parents) into more durable low-solubility waste forms.

Recycle of separated transuranics for transmutation would accomplish little in terms of reducing long-term dose, except possibly for Np-237 in an unsaturated repository. To reduce long-term doses by transmuting Tc-99, Cs-135, and I-129, thermal or epithermal neutrons are needed, as could be available in LWR and ATW transmutors. However, if low-solubility waste forms of the important radionuclides are available, reducing the inventory of these radionuclides by a few factors of ten or so does not necessarily affect the peak doses, as long as enough of each species is present to saturate the aqueous film that eventually contacts the waste form containing that species. In fact, the proposal to increase the repository capacity by transmuting heat-generating transuranics and to decrease the inventory of Np-237 by transmutation could increase the number of waste containers and actually increase the long-term dose from Np-237. Even if Np-237 inventory is not reduced by transmutation, sequestering the Np-237 into a separate and more stable waste form of lower solubility can result in lower long-term radiation dose.

190

3.3. Radiation doses from intervention

Future human intrusion into a repository, as by exploratory drilling or for other reasons, and disruptive events, such as earthquakes, meteorite impact, magma intrusion, can cause a portion of the repository contents to be directly transported to the surface or injected into flowing ground water. These events can occur early in life of the repository, as well as at later times, and they could extract radioactivity directly from the waste package. Here plutonium and americium isotopes could be main contributors to hazards. Such events have been analyzed for the Waste Isolation Pilot Plant (WIPP) in New Mexico, U.S. Consideration of human intrusion intersecting a single waste package at Yucca Mountain has been proposed. However, regulatory requirements based on protecting public health from such intervention are not yet defined. If exposure of future humans directly to the contents of a waste package at any time after repository loading is to be considered, external exposures from Cs-137 and other fission products could be important. Internal exposures could be dominated by Sr-90, Cs-137 and plutonium and americium isotopes. Transmutation of transuranics, as proposed by the ALMR project, would seem to benefit repository performance in this regard after the more intense fission products have decayed. However, according to the time-dependent inventory reduction analysis of Section 2.2, a substantial portion of the transuranic inventory would still exist above ground in ALMR or LWR transmutors and associated reprocessing facilities for a few thousand years at steady power. Accidental or willful intervention of this enormous amount of radioactivity could be more hazardous than intervention into a repository containing spent fuel.

3.4. Reducing decay heat by transmutation

Elimination of all transuranics in repository waste would reduce heat generation relative to spent fuel. At ten years after discharge the transuranics in spent fuel contribute 20 percent of the heat generation by radioactive decay, 60 percent at 100 years and 99 percent at 300 years. If this reduction is coupled with sequential waste emplacement after transmuting the transuranics, the capacity of a given repository site, measured in terms of equivalent electrical energy generation, could be increased by about fivefold. However, it has been pointed out that the design capacity of Yucca Mountain is limited by political agreement, not by area. Also, techniques other than transmutation could increase the capacity of a given site, such as sequential loading of unreprocessed spent fuel of different ages.

4.   GENERATION OF OTHER WASTE

In spite of claims by ALMR and ATW proponents, all transmutation systems reviewed here would yield products from reprocessing, maintenance, and decommissioning that would contain enough radioactivity to require disposal in a geologic repository. All transmutation systems would generate greater quantities of low-level and TRU waste than that for the once-through LWR fuel cycle.

5.   INSTITUTIONAL AND ECONOMIC ISSUES

DOE and its contractors expect that transmutor systems will be adopted by the electrical utility industry as economic alternatives to once-through power-generating LWRs. LANL adds thorium to its ATW transuranic fuel to lower the fuel cost. However, choosing and deploying a transmutor system to simplify waste disposal would be far more complicated for a utility than merely selecting a new nuclear power plant. For example, to accomplish DOE's program goals for transmutation in the U.S., about 30 GWe generated from about 22 ALMR transmutors of 0.65 conversion ratio would be required. The 63,000 Mg of LWR discharge fuel, now destined for Yucca Mountain, would be reprocessed to supply transuranics to start the ALMR transmutors and to supply make-up transuranics during their operating life.

The many different utility owners would have to agree to construct and operate not only the first-generation transmutors but also the many generations of replacement transmutors until the desired

reduction in transuranic inventory is achieved. Each of these ALMR transmutors would have its own integrated pyrometallurgical reprocessing plant, at a scale generally considered too small for economical reprocessing, a kind of operation not heretofore experienced in the utility industry. Even before any first-generation transmutors were built, new facilities to reprocess LWR spent fuel would have to be constructed, with a total capacity of 2,700 Mg/year and with an entirely new chemical process. The total capacity would exceed that of any commercial reprocessing facility yet constructed. To accomplish the transmutation schedule proposed by DOE's contractors, the above commitments must be in hand within the next few years.

The costs of development of any of the transmutation concepts would be large, but the financial risks of such large commitments are even more formidable. Cost estimates from the transmutor programs do not seem reliable, particularly in the area of reprocessing. DOE contractors' recent cost estimates for even conventional aqueous reprocessing are over fourfold lower than recent costs for contemporary facilities in other countries. Extrapolating those contemporary costs to a reprocessing facility in the U.S., and with no allowance for additional costs for high-yield recovery and multiple recycle, we estimate that the cost of U.S. reprocessing the 63,000 Mg of U.S. LWR spent fuel, based on costs of contemporary facilities and optimistically neglecting the necessary additions for high-recovery separations, would be $133 billion for commercial ownership, or $51 billion for government ownership, far greater than the presently expected cost of the geologic disposal program. We estimate a large additional cost for fabricating MOx fuel. It is likely that the new technological features and problems associated with deploying any of the transmutation concepts, as outlined above, would add even more to the total cost. Only a small fraction of this reprocessing/fabrication cost could be offset by reducing the amount of make-up uranium fuel below that required to fuel once-through LWRs. Claims by ALMR transmutor proponents that new pyrometallurgical high-recovery reprocessing techniques would reprocess LWR fuel at far lower cost, sixfold less than what we estimate for costs of contemporary aqueous reprocessing plants, are yet to be proven.

To be an appreciable benefit to waste disposal, any transmutation plan must be initiated and operated as an integrated total system. It does little good to build transmutors without suitable facilities for reprocessing and fuel fabrication. Siting and transportation issues must be faced for the entire transmutation system. These problems of system integration have not been faced by transmutation proponents; they are particularly formidable in the present climate in the U.S.

It would take massive commitments and guarantees by the federal government to ensure the success of such a large and complicated project even on a more relaxed schedule than would be required to transmute the U.S. spent fuel now destined for geologic disposal. It seems prudent instead to do the technical work necessary to ensure the success of geologic disposal of spent fuel. Some modest focused effort on transmutation systems is warranted, particularly on developing low-cost reprocessing, until it is learned whether geologic disposal needs and can profit by waste transmutation.

6.   CONCLUSIONS

After considering the information summarized above, our committee reached the following conclusions about the feasibility of reprocessing and transmutation and the impact on the U.S. repository program:

1.   Separation and transmutation (S&T) of transuranics and certain long-lived fission products in spent reactor fuel is technically feasible and could, in principle, provide benefits to radioactive waste disposal in a geologic repository. However, to begin to have a significant benefit for waste disposal, an entire S&T system consisting of many facilities would have to operate in a highly integrated manner for several decades to hundreds of years. The deployment of an S&T system that is extensive enough to have a significant effect on the disposition of the accumulated LWR spent fuel would require many tens to hundreds of billions of dollars and take several decades to implement.

2. The proposed S&T systems would require decades to centuries to achieve a significant net reduction in the total TRU inventory relative to that of a once-through LWR fuel cycle.

3. The S&T systems differ widely in their state of technological maturity and present a broad spectrum of development issues, risks, costs, and schedules. The most mature system concept for transmuting transuranics and fission products, based on the use of LWRs, needs fuel-cycle development and would require significant financial resources and enormous institutional commitment to reach the point of deployment. The ALMR/IFR system for transmuting transuranics would require even more financial resources and take longer to reach deployment. The ATW concepts would require major development before even the technical feasibility and chances of success can be realistically assessed.

4. There is no evidence that application of transmutation and its associated advanced reprocessing holds sufficient merit for the U.S. to delay the development of its first nuclear waste repository to contain commercial spent fuel. Even if a transmutation system were in place, a geologic repository would still be needed.

5. Application of reprocessing and transmutation does not hold sufficient merit to abandon the once-through fuel cycle in the U.S.

6. While the need for a second repository could be delayed by reprocessing and transmutation, there are several other ways, both legislative and technical, to increase the capacity of the first repository by a comparable amount.

7. RESEARCH AND DEVELOPMENT NEEDS

There is no immediate need for the U.S. to deploy any of these proposed technologies for separations and transmutation, primarily because there is no present indication that S&T is necessary for the repository program to meet its goals. The U.S. repository program is expected to be of long duration. The high cost of reprocessing and fabrication of recycle fuel is unfavorable in the current era of low-cost uranium and enrichment. Therefore, research and development on S&T cannot be viewed as urgent. For the near future in the U.S., S&T is best regarded as a contingency option. On the other hand, implementation of reprocessing/S&T could become desirable under a variety of situations. These could include a change in the economic viability of reprocessing and recycling in the U.S., new technical problems in meeting regulatory guidelines for a spent-fuel repository for geologic disposal, and the need for increased nuclear energy to ameliorate the climatic impacts of other energy production technologies. Therefore, it is desirable to sustain a modest level of research and development on S&T technology, with emphasis on its benefit to the repository program and on the development of efficient low-cost separation technologies.

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RADIOLOGICAL AND ENVIRONMENTAL ASPECTS
OF FAST REACTOR FUEL CYCLE FACILITIES

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Abstract

Availability of energy is an important prerequisite for the socio-economic development of any country. As the sources of fossil fuels are dwindling fast, India will have to look for nuclear power to secure a stable supply of energy. The Indian nuclear power program aims at large scale utilization of its vast thorium resources. The energy potential of uranium increases by 150 times and that of thorium by three times through the fast breeder reactor route compared to thermal reactors. This long term objective of thorium utilization is sought to be achieved through three stages of development. In the first stage a series of PHWRs will be constructed for power generation which will incidentally generate plutonium. The second stage consists of FBRs with plutonium as the fuel and thorium as the blanket. In the third stage, U-233 will replace plutonium as the fuel for FBRs. It is interesting to compare the radiological and environmental safety aspects of fast reactor fuel cycle involving U-Pu and Th-U. While uranium ore has to be extracted from deep mines thorium ores are available as surface deposits. Both occupational and environmental exposures during mining and milling operations are less in the case of thorium than in the case of uranium. Further the occupational risks related to industrial accidents are higher by a factor of three in the underground mining of uranium than in surface mining activities. It is also estimated that that the long term dose commitment from wastes from mining operations is higher in the case of uranium than in the case of thorium. During the fuel fabrication stage design provisions and administrative controls have to be made to control the exposures which result from the surface gamma dose rates on the separated Pu and U which increase as a function of time. One of the main drawbacks of the thorium U-233 fuel cycle is the presence of hard gamma emitters (2.5 Mev) among the daughter products of U-232 which is always present with U-233. Fast reactors are well known for their low occupational exposures and insignificant releases of radioactivity to the environment. According to UNSCEAR 1993, the annual effective doses to most exposed individuals in the environment for a model site are estimated to be 1 uSv for PWRs, 7 uSv for BWRs, 10 uSv for HWRs and 0.1 uSv for FBRs. High level wastes resulting from the reprocessing of irradiated plutonium from fast reactors contain nine times more of alpha emitters compared to thermal reactors. The distinct advantage of the thorium fuel cycle lies in the fact that it produces significantly less quantities of long lived minor actinides than the uranium fuel cycle.

1. INTRODUCTION

Availability of energy is an important prerequisite for the socio-economic development of any country. As the sources of fossil fuels are dwindling fast, India will have to look for nuclear power to secure a stable supply of energy. Table I gives a summary of the commercial energy sources in India. It is clear that Indian nuclear power program should aim at large scale utilization of its vast thorium resources [1,2]. The energy potential of uranium increases by 150 times and that of thorium by three times through the fast breeder reactor route compared to thermal reactors. This long term objective of thorium utilization is sought to be achieved through three stages of development. In the first stage a series of PHWRs will be constructed for power generation will incidentally generate plutonium. The second stage consists of FBRs with plutonium as the fuel and thorium as the blanket. In the third stage, U-233 will replace plutonium as the fuel for FBRs. Radiological and environmental safety aspects of fast reactor fuel cycle involving U-Pu and Th-U are discussed. While considerable experience has been gained with the operation of U-Pu fuel cycle facilities, the experience with thorium fueled reactors and associated facilities has been very limited. Hence, it is not possible to arrive at a realistic quantitative assessment of the health and environmental impact of the thorium fuel cycle. However, the factors that have to be taken into account while calculating the radiological impact and the significant differences between thorium and uranium fuel cycle at various stages of operations are discussed here.

TABLE I.   COMMERCIAL ENERGY RESOURCES IN INDIA

		Electricity Generation Potential			
Resources	Amount	Coal equivalent in billion T	GWe-Yr	Capacity Gwe	No. of years at CF 70%
Coal	190 bt	190	27,000*	350	110
Oil	0.6 bt	1.2	not to be used for power generation		
Natural Gas	540 bm³	1	280	10	40
Hydroelectricity	84 GWe at 60% CF	0.2/y	renewable	84	renewable (60% CF)
Uranium	60,000 t				
PHWR		1.2	340	15	30
FBR		195	16,000	350	65
Thorium	320,000t				
Thermal Breeders		360	70,000	350	285
FBR		1,000	200,000	350	820

* 50% Coal reserved for non electricity generation use

2.   MINING AND MILLING

Mining and milling operations contribute to 25% of the total occupational dose in the uranium based LWR fuel cycle. While uranium ore has to be extracted from deep mines thorium ores are available as surface deposits. Both occupational and environmental exposures during mining and milling operations are less in the case of thorium than in the case of uranium. The major source of occupational exposure in the case of uranium mining is from radon and its daughter products in the underground mines. Further the occupational risks related to industrial accidents are higher by a factor of three in the underground mining of uranium than in surface mining activities. A comparison of the wastes arising from mining of uranium and thorium is shown in Table II [3]. It can be seen that the long term dose commitment is higher in the case of uranium than in the case of thorium. However one should consider the increased toxicity of thorium mill tailings due to the presence of Th-230 and its daughter products, which will contribute significantly to the long term global dose [4].

3.   FUEL FABRICATION

Surface gamma dose rates on the separated Pu increase as a function of time and the increase can be a factor of two over a period of one year [5]. It is worth noting that Pu-238 which contributes maximum to the surface gamma dose rate gets burned out in FBRs. In view of the high radiotoxicity of plutonium, the fuel fabrication operations are required to be carried out in high integrity containment facilities. One of the main drawbacks of the thorium U-233 fuel cycle is the presence of hard gamma emitters (2.5 Mev) among the daughter products of U-232 which is always present with U-233. As shown in Table III [6], The dose rate on the recovered U-233 increases rapidly with time. This necessitates shielded facility for manufacture of U-233 based fuels.

4. REACTOR OPERATION

Fast reactors are well known for their low occupational exposures, and insignificant releases of radioactivity to the environment. As can be seen in Table IV, the occupational exposures from operation of fast reactors are less than in the case of thermal reactors [7,8,9]. According to UNSCEAR 1993 [10], the annual effective doses to most exposed individuals in the environment for a model site are estimated to be 1 μSv for PWRs, 7 μSv for BWRs, 10 μSv for HWRs and 0.1 μSv for FBRs.

TABLE II.   RADIOLOGICAL DATA ON WASTES ARISING FROM MINING OF URANIUM AND THORIUM

	Uranium	Thorium
Product	1 T	1 T
Ore Mined	~ 1000 T	210 T Monazite Sand
Waste Form & Mass	Tailings ~ 1000 T	(Pb Ba) sulfide 75 T
Alpha Activity	~ 2.6 TBq	0.15 TBq
Collective Dose over 10000 years (UNSCEAR,1993)	0.75 manSv	~ 0.04 manSv (estimated)

TABLE III.   DOSE RATE (mGy/h) FROM 1 kg OF U-233 AT A DISTANCE OF 30 CM

Aging Time (days)	^{232}U content in ^{233}U	
	100 ppm	1000 ppm
10	0.8	8
100	14.0	140
1000	100.0	900

TABLE IV.   OCCUPATIONAL EXPOSURE FROM REACTOR OPERATIONS

Reactor	Exposure man Sv/GWe
Phoenix (fast)	0.29
PFR(fast)	0.75
BN-600 (fast)	1.0
LWRs (thermal)	3.1

197

5. FUEL REPROCESSING

In the case of reprocessing of fast reactor fuel the concentration of fissile material and fission products in the head-end is much higher than in the case of thermal reactor fuel. A few drops of solution from the equipment in the head-end would give beta dose rates in the range of 50 Gy/h and great care is needed in the design, operation and maintenance of these equipment [5]. Material volume handled being low in the case of fast reactor fuel cycle, process equipment designs lend themselves well to criticality control through safe geometric configurations. As far as reprocessing of irradiated thorium is concerned, the use of solvent extraction technique has been well established for efficient recovery of U-233.

6. RADIOACTIVE WASTE DISPOSAL

High level wastes resulting from the reprocessing of irradiated plutonium from fast reactors contain nine times more of alpha emitters compared to thermal reactors [11]. The greatest advantage of the thorium fuel cycle lies in the fact that it produces significantly less quantities of long lived minor actinides than the uranium fuel cycle. Table V gives the inventory of minor actinides in uranium and thorium fuel cycles [12]. The two nuclides which are of environmental concern and which are significantly present in the waste streams are Pa-231 and Np-237. The behaviour of these radionuclides in the process streams and their transport characteristics in the environment need further investigations.

TABLE V.   PRODUCTION OF MINOR ACTINIDES IN URANIUM AND THORIUM FUEL
CYCLES IN g/T HEAVY METAL AT GWd/T

Different Fuel Compositions				
Minor Actinides	$235U+238U$	$235U+232Th$	$233U+238U$	$233U+232Th$
$237Np$	9.0E+02	9.6E+02	1.2E+02	2.7E+01
Am	4.7E+02	1.3E+00	5.5E+02	8.5E-03
Cm	2.2E+02	3.0E-01	2.9E+02	1.4E-03

7. CONCLUSIONS

As India is having very large deposits of thorium, major thrust is given to development of science and technology related to thorium utilization. Ever growing demand for electricity in India during the coming decades, will have to be met by substantial contribution from nuclear power and it is important to exploit the thorium resources for this purpose. Significant experience has been gained in mining, milling of thorium, fabrication of thorium and U-233 fuel, irradiation of thorium in reactors and chemical separation of U-233. Th-U fuel cycle results in very low occupational and environmental exposures compared to U-Pu fuel cycle. More importantly, the absence of long lived actinides of environmental concern is a distinct advantage of the thorium fuel cycle.

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SESSION V

.

SAFEGUARDING OF LARGE SCALE REPROCESSING AND MOX PLANTS

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Abstract

In May 97, the IAEA Board of Governors approved the final measures of the "93+2" safeguards strengthening programme, thus improving the international non-proliferation regime by enhancing the effectiveness and efficiency of safeguards verification. These enhancements are not however, a revolution in current practices, but rather an important step in the continuous evolution of the safeguards system. The principles embodied in 93+2, for broader access to information and increased physical access already apply, in a pragmatic way, to large scale reprocessing and MOX fabrication plants. In these plants, qualitative measures and process monitoring play an important role in addition to accountancy and material balance evaluations in attaining the safeguard's goals. This paper will reflect on the safeguards approaches adopted for these large bulk handling facilities and draw analogies, conclusions and lessons for the forthcoming implementation of the 93+2 Programme.

1. SAFEGUARDS IN DEPTH, AN IMPLEMENTATION OF 93+2 PRINCIPLES

The handling of plutonium in Reprocessing and MOX fabrication plants gives rise to particular safeguards sensitivities. In the early days, the safeguarding of these plants was based on the fundamental approach of material accountancy verifications complemented by NDA, C/S and monthly inventory verifications. Although time consuming and costly for the safeguards authorities and the operators, this approach was effective for small, non-automated facilities. However, the arrival of large throughput, highly automated plutonium handling plants (such as the Thorp, UP2-800, UP3 reprocessing plants and the MELOX and SMP and PFPF MOX fuel fabrication plants) heralded an era of evolution in their safeguards approaches. The number and diversity of plutonium handling facilities operated in Japan and Europe over the past 30 years has led to the accumulation of a wealth of safeguarding experience. The trend has been for the safeguards approach to become increasingly plant specific in nature, more pervasive in depth and more cognisant of the technical evolution of the reprocessing/recycling industry. This has resulted in the development of new and novel techniques, systematically integrated in a modern global approach, based on the concept of "transparency" as opposed to a mass balance "black box" concept. The trend is set to continue in the Japanese Rokkasho-mura reprocessing plant and is likely to include other evolving plant tracking techniques such as solution/tank monitoring.

The International Community examined the safeguarding of large scale reprocessing plants in the IAEA LASCAR forum in the late 80's, and concluded that, "appropriate combinations of the many possible techniques identified for safeguards measures, coupled with timely efforts in the examination and the verification of design information, make possible the implementation of effective and efficient safeguards". Many of the issues raised in those International discussions have

been directly addressed and the safeguards approach adopted for current facilities are fully consistent with the conclusions of the LASCAR forum. For example, sound, practical solutions have been found in the areas of construction verification, commissioning activities and authentication amongst others. The result is a scheme which provides, "an assurance far superior to the assurance of detection which can be generated from classical material balance concepts". The new generation of MOX plants have built on these approaches, and on the experience gained since the world's first thermal MOX fuel was loaded in Belgium in 1963. The key to this process was communication and co-operation between the operator and the safeguards authorities. Also critical were the effective R&D efforts at national and international level resulting in notable achievements in the areas of measurement techniques, C/S and monitoring.

Therefore, the reality today is that specific approaches are implemented in reprocessing and MOX plants, tailored to take maximum benefit from the features of those plants : automation, computerised systems, unattended monitoring, etc. The solutions adopted clearly anticipated the need for more qualitative, information rich and open approaches which are the corner-stones of the 93+2 principles of additional information, additional access, and remote monitoring. A real concept of transparency is apparent from the wealth of information provided, which gives additional assurance from a system of "safeguards in depth".

1.1. Additional access to information

Information technology can now encompass a much broader set of data in assessing a State's nuclear activities, on a different scale to that contemplated when safeguards agreements such as INFCIRC 153 or Euratom regulation 3227/76 were drafted. A wide range of information is provided by the operator to the inspector for modern plants:

(a) Plant design information has been provided in great detail from the conceptual stage of plant design through construction. This is continually updated and authenticated throughout production operations. Early consultations with the Safeguards authorities enable their requirements to be encompassed in a more effective and efficient manner.

(b) Plant process operational data is subject to independent monitoring (either by separate instruments or by branching operator's equipment) and is subject to random verification together with short notice verification of plant design information. This provides effective safeguards far beyond that which NMCA and traditional C/S can achieve;

(c) Extended data access, with inspector access to operator computer systems and transfer of data in real time or near real time, to the inspectors computers. These data are in addition to that required monthly in accounting reports and provide inspectors with a clear view of what is actually going on in the process. This allows continuity of knowledge to be maintained throughout the process and any abnormal process conditions to be clearly observed. The operating data set is validated for consistency and verified at different levels at chosen points. In this way a powerful assurance is built up irrespective of the material balance area structure agreed for the facility.

The analogy here is with the expanded declaration, where declared activities are compared with reality in order to gain a qualitative rather than quantitative assurance. Other notable "non quantifiable" aspects include continuous inspection by inspectors who are very knowledgeable about the plant, its operations and its data generation. Such an open, information rich environment gives a virtual guarantee that any attempts to falsify data would be detected.

As an example, consider the safeguards scheme in the MELOX MOX fabrication plant in France which verifies the internal/external flows and inventories on a continuous basis. Audit of the operating and accountancy records is facilitated by a daily declaration from the plant's centralised computer system, together with data from independent unattended measurements. The verification

and re-verification of Basic Technical Characteristics validates such things as the design of the plant, the route followed by the nuclear material, the man machine interface and the generation of data from the operator's computerised system etc. The Safeguards scheme in the SMP Sellafield MOX Plant employs essentially the same principles and practices but has been tailored to take account of the closely coupled powder process equipment which is monitored using statistical evaluation software (Near Real Time Material Accountancy, NRTMA) and real time continuous inventory measurements from in-line weighing and NDA. The NRTMA technique is also utilised in the PFPF MOX plant in Japan and will be a key element of the approach for Rokkasho-mura. NRTMA, underpinned by efficient data acquisition and transfer software, provides a powerful plant monitoring tool open to independent verification. Unattended instruments incorporated in the automatic process equipment in these large bulk handling plants gives the safeguards inspectors both quantitative and qualitative information on material flowing The independent knowledge of the flow is such that it allows derivation of minimum residence time of nuclear material and hence the minimum stocks in the areas in order to maintain flow. A clear continuous knowledge of work in progress is a much better parameter for timely assessment of any misuse scenarios.

1.2. Additional physical access

To a large extent, operators have eliminated any barriers limiting the access by inspectors to the plant. In INFCIRC 153, a number of strategic points have to be agreed upon between Safeguards Authorities and the operator. Inspector access has been in principle limited to such points. However, the practice today in large Pu bulk handling facilities is to grant access to all points in the process except where restrictions need to be maintained for safety or radiological protection reasons. Access to the external areas of the plant may also take place to verify containment integrity. Moreover, randomisation and short-notice inspections are being accommodated and unannounced access is foreseen. Again take the example of MELOX where all in process material can be selected for interim verification (identification, weighing and NDA). Greater physical access to process also takes an unattended form as in the case of SMP where material passes through unattended in-line safeguards instruments which measure 100% of the material flowing. At many nuclear sites such as Sellafield, the access and escorting of inspectors has been reviewed with the aim of simplification and greater flexibility. Inspectors also have increased access to review plant modifications in order to maintain comprehensive knowledge of the plant and to maintain the credibility of the safeguards arrangements.

1.3. Remote monitoring

Unattended monitoring in safeguards offices on-site but remote from plant operations, plays an important role at reprocessing and MOX fabrication plants. From their offices inspectors can evaluate these data (from neutron and gamma unattended stations, branched operator's equipment, analytical labs, etc.) coming direct from plant via a protected network, against the more traditional declarations. Significant savings in time for both operators and inspectors are obtained and a high level of deterrence is achieved. The operator does not know which part of its process is actually monitored by the inspectors at any given moment, and the inspector can record all or part of the information even when he is absent. Using their on-site computers and software, they can perform any analysis or calculations necessary to ensure that the plant is operating as declared. Work is underway to develop software to analyse such monitoring data on a continuous basis , to enable the inspector to derive the full potential of this verification measure. The nearly continuous presence of inspectors on site provides a rapid feedback to the operator so that any anomalies can be detected and resolved in a very timely fashion. Extending remote monitoring to safeguards headquarters is of course also possible for static devices or remote activation of instruments but this offers little practical advantage for plants under continuous inspection.

1.4. Increased co-operation and enhanced training

Over the last twenty years nuclear fuel cycle operators have increased their efforts to build confidence. Safeguards and non-proliferation issues are now seen as crucial business drivers and international safeguards verification is an essential prerequisite in the pursuit of nuclear trade. A policy to promote greater public awareness has also been accompanied by an open policy to requests from safeguards inspectors for data and information, far beyond the usual interpretation of regulatory requirements. In order to facilitate such openness and transparency it has been necessary to re-examine both the traditional security culture and the concerns over commercial confidentiality and intellectual property rights. There is no place in modern safeguards arrangements for obstruction or diffidence with the regulators, and operators are keen to ensure that safeguards assurance is fully integrated with modern manufacturing techniques. The scale of Pu bulk handling plant projects and the developments in massive containment, automation and real time data acquisition have been recognised by the Safeguards Authorities who have risen to the challenge to update the traditional safeguards approaches. Thus the seeds of the modern collaborative process were sown and a strong joint safeguards project management structure, regular communications and close integration of safeguards requirements with the overall project plan have become the norm for all new plants. This close collaboration also encompasses training, with operators offering extensive training to safeguards inspectors to increase understanding of plant and equipment operations. Both sides recognise the need to deploy specialists staff and to maintain a high level of understanding and competencies. Special precautions have been taken to provide a pragmatic solution to information exchange which does not compromise security, commercial confidentiality or intellectual property.

1.5. Improved cost-effectiveness

The approaches for Pu bulk handling plants are well established and the operators, and Safeguards Authorities, can see the benefits. The Safeguards Authorities have invested heavily in developing and installing advanced elaborate verification systems and have worked closely with the operator to take maximum benefit from plant features and to utilise operator equipment (which has been independently authenticated and validated). In this way, short term capital investments will free longer term manpower resources whilst at the same time increasing detection capabilities. These investments also include on-site laboratories at La Hague and at Sellafield , thus giving the opportunity to reduce sample transport and handling costs, and to allow timely analytical results to take their place in the near real time on-site monitoring.

These advances in effectiveness have been implemented willingly by States and operators who are committed to further progress in order to improve efficiency. This may be realised in the coming years, when additional experience is accumulated and new technologies and improvements are put in place. Measures introduced as a precaution in the present safeguards approaches may be simplified, and technical progress will permit an increasing degree of automation in the measurements and real time surveillance of these facilities. The positive experience of these approaches in Pu facilities will lead to the adoption of similar approaches in other types of facilities handling indirect use materials. Such approaches are of course initially capital intensive and it will be necessary for the international community to provide an adequate level of funding.

2. THE NEXT STEP

New measures are largely implemented on top of the more traditional measures, rather than instead of them, this results in a degree of redundancy. The safeguards authorities could not reduce more traditional verification before the 93+2 program was officially adopted. Following the implementation of the 93+2 measures then this redundancy could be avoided by relaxing some of the traditional verification, given the added assurances from the "safeguards in depth" and 93+2

approaches. The safeguards authorities and the international community are considering this question, but the most pressing challenge is how to adapt/evolve the safeguards criteria to gave full credit to the new approaches and to give safeguards assurance over and above that derived from purely quantitative evaluation criteria. The holy grail should not be to attempt to quantify the qualitative data provided by safeguards in depth and 93+2 approaches but to build a body of evidence on which a qualified judgement can be made. The case of deep repositories (where material balances cannot be closed by physical inventory taking) is a good example. In this case material accountancy cannot be applied and verified in the usual manner and the criteria must place more reliance on C/S measures.

3. CONCLUSION

With the implementation of a network of verification/authentication measures using various levels of independence, the International Community has continuous assurance that plutonium bulk handling plants are used only for peaceful purposes, and that the LASCAR conclusions have been borne out in reality. The "Safeguards in depth" approach is not a new initiative but a natural evolution gained from considerable experience in defining, assessing and implementing tailored safeguards in automated, bulk handling facilities.

This paper has shown that the 'safeguards in depth' approach has been a forerunner of the 93+2 initiatives. Whilst a large element of 93+2 is aimed at detecting clandestine nuclear sites, the methods used in safeguarding large scale reprocessing and MOX plants and the hierarchy of 'un-quantifiable' measures can give very powerful safeguards assurance that there are no undeclared materials/activities on declared nuclear sites .

It is the increased level of information and access that has brought this assurance. Transparency is the aim and close co-operation is the vehicle to achieve it. The challenge to the International Community is how effectively this plant level experience can be extended at the State level and how the IAEA is going to derive its conclusions. Qualitative elements are likely to become the predominant factor in drawing such conclusions in future.

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SAFEGUARDING OF SPENT FUEL CONDITIONING AND DISPOSAL IN GEOLOGICAL REPOSITORIES

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Abstract

Disposal of spent nuclear fuel in geological formations, without reprocessing, is being considered in a number of States. Before disposal the fuel will be encapsulated in a tight and corrosion resistant container. The method chosen for disposal and the design of the repository will be determined by the geological conditions and the very strict requirements on long-term safety. From a safeguards perspective spent fuel disposal is a new issue. As the spent fuel still contains important amounts of material under safeguards and as it can not be considered practicably irrecoverable in the repository, the IAEA has been advised not to terminate safeguards, even after closure of the repository. This raises a number of new issues where there could be a potential conflict of interests between safety and safeguards demands, in particular in connection with the safety principle that burdens on future generations should be avoided. In this paper some of these issues are discussed based on the experience gained in Germany and Sweden about the design and future operation of encapsulation and disposal facilities. The most important issues are connected to the required level of safeguards for a closed repository, the differences in time scales for waste management and safeguards, the need for verification of the fissile content in the containers and the possibility of retrieving the fuel disposed of.

1. INTRODUCTION

Spent nuclear fuel still contains important amounts of uranium and plutonium that could be reused as fuel. The original plans in most countries were thus that the fuel should be reprocessed and that the material should be recycled in nuclear reactors. Since some years now, however, a growing number of countries are considering to dispose of all or some of its spent nuclear fuel as waste, directly without reprocessing. This was not foreseen when the existing safeguards regime was created. The disposal of spent nuclear fuel thus raises a number of issues connected to the safeguarding of the fuel during handling, storage, conditioning and disposal. In this paper some of these issues will be discussed.

The disposal route foreseen for long-lived radioactive waste in most countries is disposal at depth in geological formations. This is also the disposal method foreseen for encapsulated spent nuclear fuel. Research and development work as well as siting activities are going on in many countries and it could be foreseen that some repositories for spent nuclear fuel will be in operation in about 10 - 20 years from now.

Before disposal the spent fuel will be conditioned by encapsulation in a tight and corrosion resistant container. The method chosen for disposal will be determined by the very strict requirements on the long-term safety of the repository. In the IAEA Safety Fundamentals Report on "The Principles of Radioactive Waste Management" [1] it is stated that:

"The objective of radioactive waste management is to deal with radioactive waste in a manner that protects human health and the environment now and in the future without imposing undue burdens on future generations."
and that:
"Conflicting requirements that could compromise operational and long term safety should be avoided"

209

The ethical principle underlying these statements is that the generation that benefits from the nuclear production and produces the waste shall bear the responsibility for managing the waste. At the same time it is also clear that it would not be ethical to deprive the future generations of their right to retrieve the material if they so wish. The reason for this could be to reclaim the energy resource still available in the fuel or to improve the isolation of the waste.

In particular the fact that no undue burdens must be imposed on future generations can be interpreted such that the repository should be designed so that it will not require any long-term control for safety reasons. It does not, however, exclude the possible use of institutional control arrangements, e.g. for safeguards reasons as long as they do not impair the safety of the repository. Also from a safety point of view it might be of interest to continue monitoring the repository for some period of time, not least with regards to public acceptance.

To achieve the required level of safety, the repositories will be designed in such a way that the spent fuel will not be easily accessible for direct safeguards control. In most designs, however, it will still be possible to retrieve the fuel long after disposal, even if this will require a substantial effort.

The spent fuel still contains important amounts of material under safeguards. The IAEA has therefore commissioned a number of studies on the need for safeguards during and after the conditioning and disposal of the spent nuclear fuel. In 1988 an Advisory Group meeting [2] reached the following conclusion:

"...that spent fuel does not qualify as being practicably irrecoverable at any point prior to, or following, placement in a geological formation... and recommend that the IAEA should not terminate safeguards on spent fuel."

This implies a potential conflict of interests between safety and safeguards, as regards the need for control after closure and the possible burdens on future generations. This might be true with regard to traditional safeguards. However, with the evolving picture about modern safeguards it is clear that the potential conflict can be resolved. It was also concluded at a Consultants meeting of the IAEA in 1995 [3]:

" Not withstanding the eventual large fissile material inventories involved, and the wide variation in the form of repositories, the consultants concluded that there are techniques and methods which can be deployed such that the IAEA will be able to derive appropriate safeguards assurances."

In this paper some of the key issues of safeguards for conditioning and disposal of spent nuclear fuel are discussed and some examples are given about the approach made in particular in Germany and Sweden.

2.   SOME SYSTEMS FOR SPENT NUCLEAR FUEL DISPOSAL

2.1.   General overview

Disposal of spent nuclear fuel is considered in e.g. the US, Canada, Finland, Germany, Spain and Sweden. Studies are going on also in other countries. All the concepts studied have the common approach that the spent fuel will be encapsulated in a tight container and that the container will then be brought down into a repository at great depth, 500 - 1000 m, in a geological formation. The tunnels or shafts will then subsequently be backfilled and closed. Before encapsulation the fuel will be stored for 10 years or more. During this period the radioactivity and the heat output decay and the emplacement of the waste in the repository can

be made more efficiently, as most repositories are limited by the maximum allowed temperature in the rock, and thus by the decay heat of the fuel at the time of disposal.

The management of spent nuclear fuel for direct disposal will comprise the following components:

- *Storage at reactor.* After removal from the reactor core the fuel will be stored in the spent fuel pools at the reactor for at least almost a year and in many cases for ten years or more.

- *Transport.* The fuel will then be transported to an interim storage facility in heavy shielded transport casks.

- *Interim storage.* Different types of interim storage facilities are in operation. In Germany e.g. the fuel is stored in the same casks as are used for transport and thus no handling of fuel assembly is made at the storage facility. In Sweden the spent fuel is removed from the transport cask at the interim storage facility and stored in deep water pools. Also dry storage facilities exist where the fuel is transferred from the casks to a storage area, either as separate and identifiable fuel assemblies or inside a sealed canister. In some cases the fuel assemblies are disassembled before storage and the fuel rods are packed closer to increase the storage capacity (rod consolidation).

- *Encapsulation.* Before disposal the fuel is then transported to an encapsulation facility, where the fuel assemblies are placed in a large disposal container that is welded tight. Until now no encapsulation facility is in operation. In Germany a pilot encapsulation facility, the so-called Pilot-Konditionierungsanlage (PKA), is in an advanced stage of construction at Gorleben. The PKA is scheduled to be in operation in 1998.

- *Disposal.* The encapsulated fuel is then transported to the repository site and transferred underground for disposal in a tunnel or vault system. When one disposal area is full the tunnels and vaults of that area will be backfilled (either directly or after a certain time). Later when all waste has been disposed of in the repository the entrance tunnels and shafts will be closed and the aboveground facilities will be removed. Until now no disposal facility for spent fuel is in operation.

For the first three steps, storage at reactor, transport and interim storage safeguards regimes have been developed and applied on a routine basis. For the encapsulation plant and, in particular, for the disposal facility new safeguards strategies and methods are being developed, since 1988, under the German Support Programme to the IAEA and, since the early 1990's, under a joint task of several IAEA Member States Support Programmes (Development of Safeguards for Final Disposal of Spent Fuel in Geologic Repositories (SAGOR)), the results of which will be presented this autumn.

The general description of the spent fuel management system for disposal given here is valid for most countries. A lot of similarities exist in the different systems studied. There are, however, certain differences that are of importance from the point of view of safeguards. These are mainly connected to the different geological media that will be used and the consequences this will have on the possibility of and the efforts needed for retrieving the fuel canisters, once they have been disposed of. In a hard rock repository e.g. the tunnel system will remain stable for a long time and retrieval could be accomplished after removal of the backfill material in the tunnels. In salt, on the other hand, the tunnels will disappear due to the creep of the salt and new tunnels would need to be excavated for retrieval. Also the different locations of a

repository with respect, for instance, to the population density will have an effect. In the US the repository is planned to be built in a desert far away from any large population clusters, while the repository in Germany will be built in a much more densely populated area (although quite sparsely populated as compared to other areas in Germany).

2.2. Plans for spent fuel disposal in Germany

In Germany spent nuclear fuel, high level vitrified waste and other long-lived alpha bearing wastes are planned to be disposed of at about 900 m depth in a salt dome at Gorleben in central Germany. A project is underway to characterise the salt dome and to investigate its suitability for a repository. Today two shafts have been sunk to about 850 m depth and they have been connected by a tunnel at that depth. According to present plans the repository at Gorleben could start operation at around 2025.

Before disposal, the spent fuel is planned to be encapsulated in a self-shielding container, the so-called POLLUX cask. This will be done in a separate facility. A pilot plant for the conditioning is under construction at Gorleben and will be in operation in 1998. The facility is called Pilot-Konditionierungsanlage (PKA). The encapsulation of spent fuel in PKA will have the following sequence [4]:

- The spent fuel arrives in combined transport and storage containers from the interim storage facility. The containers are taken into the PKA and docked to the unloading hot cell.

- In the unloading cell the fuel assemblies are removed from the container and transferred to the conditioning cell. There, the fuel assemblies are disassembled and the intact fuel rods are compacted by putting them into a bin that is transferred to the POLLUX cask. The POLLUX cask will accommodate about 5 tonnes of heavy metal.

- The POLLUX cask consists of an inner container, that is welded to make it gas tight and that constitutes the storage space and an outer container that provides supplementary shielding against radiation.

- The POLLUX cask is sealed using three lids; the primary lid is screwed on, the secondary lid is welded to the inner container and the lid of the shielding container is screwed on and secured by a weld seam.

From a safeguards perspective the PKA is an item facility, where the fuel assembly items are rebatched into disposal container items. The safeguards strategy for the facility is based on Design Information Verification and on radiation monitoring as well as containment and surveillance to ensure that no fuel is removed except in a POLLUX cask. Before the fuel assemblies are disassembled a check is also made that the content of the fuel assemblies corresponds to the declared fuel material.

The disposal container will then be transported to the repository site, and brought underground intact. The repository will consist of a set of access tunnels and disposal drifts that will be successively excavated in parallel with the disposal and backfilling of the spent fuel [5, 6, 7]. For economic reasons Gorleben is foreseen to accommodate different types of waste, such as waste with negligible heat generation, vitrified high-level waste and spent nuclear fuel in POLLUX casks. The reference spent fuel disposal concept foresees horizontal emplacement in drifts. Directly after a cask has been put in place the void volume of the drift will be backfilled with crushed salt. Due to the heat generated by the fuel and the normal creep

of the salt the drift system will be closed and inaccessible shortly after disposal. Also the tunnels leading up to the disposal drifts will be successively backfilled with crushed salt [8].

From a safeguards perspective the disposal casks thus become impossible to verify immediately after disposal. The emphasis of the safeguards system must thus be the verification of the design information (DIV) and to be able to verify the disposal cask in terms of identity and integrity as they arrive at the repository reception facility [9,10].

2.3. Plans for spent fuel disposal in Sweden

In Sweden the plans are to encapsulate the spent nuclear fuel in a container of copper and steel and to dispose of it at about 500 m depth in the Swedish crystalline bedrock [11]. The site for the repository has not yet been chosen, but a siting programme is well under way. According to present plans disposal should start around 2010 at the earliest.

Before disposal the spent fuel will be encapsulated in a tight and corrosion resistant container. The container consists of an outer copper shell (5 cm thick) that provides the corrosion resistance and an inner steel container that give the mechanical strength. One container will take about two tonnes (uranium weight) of spent fuel. An encapsulation facility is planned to be built as an extension of the existing interim storage facility, CLAB, at Oskarshamn. The following sequence will be followed:

-   The spent fuel is brought from the storage pools to a reception pool in the encapsulation plant. This is done under water in a water filled channel.

-   In the reception pool the fuel is identified and possibly measured for heat release and then brought to a hot cell where it will be dried before being filled in the disposal container.

-   The lid of the inner steel container is screwed on and then the outer copper lid is welded tight by electron beam welding.

-   After control the disposal container is put in a transport container that will provide full shielding and protection for transport.

From a safeguards point of view the Swedish encapsulation plant will have the same features as the PKA.

The disposal container will then be transported to the repository site and brought underground. There will be a tunnel or shaft down to repository depth. The repository itself will consist of a series of tunnels. The disposal of the containers will be made in shallow boreholes that have been drilled in the bottom of the tunnels. Before disposal the disposal containers will be unloaded from the transport containers that will be reused. As the dose rate of the disposal container will be 10 mSv/h or more the subsequent handling will be made remotely. In the borehole the disposal container will be surrounded by bentonite clay. From that moment no more direct control of the container is feasible. When all the boreholes (about 30) in a tunnel have been filled the tunnel will also be backfilled and a plug will be built at the tunnel entrance. The transport tunnels up to the disposal tunnels will, however, be kept open for the whole operating period of the repository, i.e. about 30 - 40 years.

From a safeguards point of view the Swedish repository will be similar to the German. One difference will, however, be that it should be easier to retrieve the disposal containers in the Swedish case as the tunnel system in hard rock will not collapse until very late.

3. KEY SAFEGUARDS ISSUES

Based on the discussion that has been going on for almost ten years within the nuclear safeguards and the radioactive waste management communities and the experiences gained from the German and Swedish studies one can identify the following key issues for the safeguards for the conditioning and disposal of spent nuclear fuel:

- *Attractiveness of the disposed fissile material in the fuel*
- *Level of safeguards measures for a closed repository*
- *Time scales of interest*
- *Conflict of interest between safety and safeguards needs*
- *Verification of fissile content in a disposal container*
- *Continuity of knowledge*
- *Strengthening safeguards*

In the following these different issues will be discussed. Most of them are coupled to the closed repository. The safeguards issues connected to the operation of the conditioning facility and the repository is considered to be fairly straightforward with the application of existing safeguards techniques.

3.1. Attractiveness of the disposed fissile material in the fuel

As spent fuel contains plutonium it is regarded as a strategic material and is subjected to strict safeguards control. The plutonium contained in spent fuel from Light Water Reactors is, however, generally not regarded to be very attractive from a proliferation point of view. The plutonium contains a large fraction of heavier non-fissile plutonium isotopes. Although it has been shown that it is possible to manufacture a nuclear explosive also with such a composition, it has no value as a weapons material. The plutonium is also intimately mixed with fission products and other transuranic assemblies in the fuel and there will be a need to reprocess the fuel in order to separate the plutonium. For this reason discussions have started to define different categories of plutonium in analogy with the various categories of uranium [12].

In particular for plutonium contained in spent fuel in a closed repository at great depth it should be of interest to investigate its potential strategic value as compared to other materials, e.g. uranium ore. Larger efforts will probably be needed to retrieve the spent fuel than what is needed for extraction of uranium. Discussions like these will undoubtedly be of importance when determining the safeguards strategy for a closed repository.

3.2. Level of safeguards measures for a closed repository

Bearing in mind the physical protective capacity of the engineered and natural barriers in a repository and the large effort required to retrieve the spent fuel from a closed repository what should be the appropriate level of safeguards measures after closing of the repository? How is a balance of the level of safeguards throughout the nuclear fuel cycle achieved, taking the nature of the fissile material into account?

The key question concerning the safeguards for the closed repository is the risk of diversion through an existing or new tunnel or by reprocessing the fuel underground and bringing the plutonium up. This question is relevant during operation as well. As the disposal containers will not be accessible after disposal the control has to rely on indirect methods. Two important components are the possibility to continue the design verification throughout the operation period and the adequate control of what is entering and leaving the access tunnels or shafts. The purpose of the design information verification is to make sure that no undeclared

activity is planned for underground and that there are no undeclared exits. Also specified equipment underground that could be used for opening the containers should be identified. This work must continue during the operation period as the tunnel system will be continuously excavated. A number of geophysical methods have been proposed but not yet approved for underground design information verification such as mobile ground penetrating radar.

As regards the control of the access tunnels and shafts it will be important to limit the number of accesses or if this cannot be done, e.g. for ventilation purposes, to design them in such a way that fuel could not be removed undetected. For the tunnels or shafts that will be used for the transport of disposal casks radiation and motion detectors in combination with optical surveillance equipment could be utilised above ground. Such dedicated safeguards techniques have not, however, been approved for application under the rugged underground conditions in geological repositories for spent fuel.

For the closed repository the control of the existing, but closed, access points is the most important, but also a control that no new tunnelling is made into the repository from somewhere in the neighbourhood. As the time needed to make a new tunnel and shaft will be typically a year or more and that such an operation necessarily will create some debris, it should be possible to detect it by satellite images and by site visits by the IAEA. It has also been considered to use seismic detectors on the surface to probe for undeclared mining activities. Although this might work in a desert environment like the Yucca Mountain site in the US, it will probably not work in a densely populated area in Germany, due to other industrial seismic noise. Also probes embedded at depth in the tunnel system or in deep boreholes have been proposed but discarded due to the risk of malfunctioning with no way of repair and to the risk of impairing the safety of the repository.

3.3. Timescales of interest

From a safety point of view the integrity of the repository will be considered for ten thousand years or more, due to the content of plutonium and other long-lived radionuclides. With this timescale a control based on assured human activities does not make sense and the safety should be fully based on the passive protecting capacity of the engineered and natural barriers. The plutonium and uranium will remain in the fuel for even longer times. What should be the timescales considered from a safeguards perspective?

The recommendation by the Advisory group in 1988 that safeguards should not be terminated on spent fuel in a repository could be interpreted that safeguards should be kept for ever. This is clearly not feasible as an assumption. The safeguards system, as presently organised, relies on active participation of humans and has only been developed to provide assurance for the present and short term future. It is a result of voluntary agreements between States and will have to be re-evaluated on a regular basis. With the level of safeguards control described in the last chapter there will be no problem in continuing the safeguards of the repository for as long as the States find it important. This was expressed by the 1995 Consultants Group meeting [3] as:

"Safeguards should continue to be applied to spent fuel in the repository as long as safeguards apply to nuclear material elsewhere."

If the projections are made very far in the future they will cease to make sense. One could for matter of curiosity consider how safeguards should be kept during a period of glaciation, which is probable to occur in Sweden in about ten thousand years.

3.4. Conflict of interest between safety and safeguards needs

The prime objective of disposal of spent nuclear fuel is the protection of the human health and environment by the safe containment of the radionuclides. There is some concern in the radioactive waste management community that the requirements for safeguarding nuclear material could compromise safety [13]. These concerns are mainly connected to the safety of the disposal facility after closure. During conditioning the safeguards approaches will only impose small, if any, problems from the safety point of view.

For the closed repository it should be imperative that the safeguards requirements on control should not be allowed to impair the barrier system. Only non-intrusive surveillance mechanisms should be utilised. Bearing in mind the large efforts needed to retrieve the disposed spent fuel and the relative unattractiveness of the fissile material it has been concluded that surveillance from the surface, e.g. by satellite images, in combination with site visits should be adequate for safeguards control.

The main conflict of interest will thus be on the more philosophical level. The fact that safeguards control contradicts one of the objectives of radioactive waste management, that is not to impose a burden on future generations, and the difficulty of making economic provisions for an activity of unknown duration.

3.5. Verification of fissile content in disposal container

As long as the fuel assemblies are handled as separate items without thick shielding it will always be possible to reverify the fissile content. After encapsulation it will no longer be possible to verify the fissile content by measurements but one will have to rely on containment and surveillance methods. Can a sufficient level of safeguards be accomplished for this case?

As the reverification will no longer be possible on the disposal container, unless the container is reopened for inspection, it will be of utmost importance to be able to apply a so-called dual containment and surveillance system. The purpose of the system should be to maintain the continuity of knowledge of the disposal container and its content from the closing of the container lid to the reception of the container at the repository entrance. The important components of this is the use of seals and the possibility to reverify the identity and the integrity of the disposal cask. The latter will be of paramount importance in order to avoid any requests to reopen the containers.

In most concepts a verification of the fuel assemblies and their fissile content is foreseen just before the fuel assemblies are put in the disposal container. The reason for this is clearly, that it will be the last opportunity to do such an inspection activity. As this measurement takes time and costs money and dose it should be strongly considered if it must be done. If disposal, as is foreseen in many States, will only be made 30 - 40 years after use of the fuel, the possible detection of any missing material at that time does not give much information about what has happened. If the safeguards measures have functioned well during the period while the fuel is in storage, the final check does not make much sense. Continuity of knowledge should have been kept.

3.6. Continuity of knowledge

It has become quite obvious from the preceding discussions that all efforts should be made to keep the continuity of knowledge of the fuel assemblies all the way from the use in the reactors via transports and interim storage to the encapsulation and final disposal. Unless this is achieved a heavy burden will be put on the capability of reverification of the material content in the fuel. This will remain possible until the fuel is encapsulated but it would require

an important work and should be avoided. To maintain the continuity of knowledge following encapsulation safeguards will exclusively have to rely on containment and surveillance techniques.

3.7. Strengthening safeguards

In 1993, a programme of strengthening and efficiency improvement for safeguards was initiated (currently known as "Programme 93+2") [14]. Implementation of the safeguards scheme under the model protocol [15] will provide the IAEA with additional information on a State's entire nuclear programme even when nuclear material is not involved (expanded declaration). Furthermore the IAEA will have increased capability to check such information and to solve inconsistencies and questions that might occur. Key components of this programme are extended access, environmental sampling, use of remote monitoring equipment and unannounced inspections.

The safeguards approaches discussed for a closed geologic repository is fully in line with the underlying principles of this new safeguards regime. With the information available about the repository and about the nuclear material deposited therein, measures described in the Draft Protocol could be applied with high confidence to the area of the repository. Detailed information about the repository would be an important element of the additional information given to the IAEA by a State about its nuclear programme and other potential nuclear resources. A repository would then be announced on a similar level as a uranium deposit.

4. CONCLUSIONS

Safeguards approaches for above ground spent fuel conditioning facilities can be designed without problems using available safeguards methods and techniques.

Safeguards for final disposal of spent fuel in deep geological repositories will be feasible. In an operating repository design information verification above and underground will be necessary to the end of detecting undeclared operations for retrieval or separation of fissile materials. Details in the applied technical means and inspection frequency may differ according to the geological formation in which a repository is located.

Provided the spent fuel disposal casks become inaccessible immediately after emplacement, nuclear material control should be restricted to the above ground part of a repository, for which approved containment and surveillance techniques exist (e.g. optical surveillance, sealing, integrity verification, radiation monitoring).

For closed repositories it will be sufficient to apply satellite sensing and periodic on-site inspections. Any other technical means discussed so far would involve the installation of sensors and probes in the ground and thus would jeopardise the long-term safety of a repository (e.g. access of water to the emplaced nuclear material).

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REGIONAL SAFEGUARDS ARRANGEMENTS: THE ARGENTINA-BRAZIL EXPERIENCE

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Abstract

A Common System of Accounting and Control of Nuclear Material (SCCC) was established by Argentina and Brazil in July 1992. It is a full scope safeguard's system in both countries. The Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC) was created to apply the SCCC. The main elements of the SCCC are presented. The main safeguards' procedures are described. A brief discussion of the inspection methodology and its impact for facility operators is performed. The safeguard's implementation from the operator's point of view is commented, taking as example a fuel fabrication plant in Argentina and a uranium enrichment plant in Brazil.

1. INTRODUCTION

The Agreement between the Republic of Argentina and the Federative Republic of Brazil for the Exclusively Peaceful Use of Nuclear Energy [1] has been in force since December 1991. The basic undertakings of the bilateral agreement are:

a) To use the nuclear material and facilities under their jurisdiction or control exclusively for peaceful purposes;

b) To prohibit and prevent in their respective territories, and to abstain from carrying out, promoting or authorizing, directly or indirectly, or from participating in any way in:

- The testing, use, manufacture, production or acquisition by any means of any nuclear weapon; and

- The receipt, storage, installation, deployment or any other form of possession of any nuclear weapon.

The Agreement also establishes that any serious non-compliance by either of the Parties enables the other party to abrogate the agreement, with the obligation to notify the Secretary General of the United Nations and the Secretary General of the Organization of American States of this fact.

To verify the control's commitment of the Bilateral Agreement the Brazilian-Argentine Agency of Accounting and Control of Nuclear Materials (ABACC) was created. The ABACC's objective is to administrate and apply the Common System of Accounting and Control of Nuclear Materials (SCCC), also established by the Agreement. The SCCC is a full scope safeguards system that is being applied in both countries with the purpose of verifying that all nuclear materials in all nuclear activities are not diverted to the manufacture of nuclear weapons or other nuclear explosive devices.

Based on the Bilateral Agreement, a Quadripartite Safeguards Agreement among Argentina, Brazil, ABACC and the International Atomic Energy Agency (IAEA) [2] was signed in December 1991. This agreement is a full scope safeguards agreement, similar to INFCIRC/153 model agreements, and entered into force on March 1994 after its ratification by the Congresses of both countries.

The basic undertakings of the Quadripartite Agreement are: The acceptance by the State Parties of safeguards on all nuclear materials in all nuclear activities within their territories, under their jurisdiction or carried out under their control anywhere, for the exclusive purpose of verifying that such material is not diverted to nuclear weapons or other explosive devices.

The IAEA, in its verification, shall take due account of the technical effectiveness of the SCCC. Furthermore,

- The State Parties, ABACC and the IAEA shall co-operate to facilitate the implementation of the safeguards provided for in the Agreement.

- ABACC and the IAEA shall avoid unnecessary duplication of safeguard's activities.

The implementation of such a complex safeguards system with its several interfaces - IAEA, ABACC, National Authorities and Operators - requires a great effort and cooperation of all parties involved. This paper describes the status of this implementation, emphasizing its relevant aspects for nuclear fuel cycle facilities.

2.   THE COMMON SYSTEM OF ACCOUNTING AND CONTROL - SCCC

The Common System of Accounting and Control of Nuclear Material (SCCC) is a set of procedures established by the Parties to detect, with a reasonable degree of certainty, whether the nuclear materials in all their nuclear activities have been diverted to uses not authorized under the term of the Bilateral Agreement.

The SCCC was conceived as a full scope safeguards system to be implemented by a central executive body (the permanent staff of ABACC), which is technically and financially supported by the Parties to carry out its duties. This system requires the concurrence of efforts of Operators, National Authorities and ABACC. The National Authorities play a significant and special role in the implementation of the SCCC: besides the usual activities at state level, each of them is the natural channel through which ABACC requires the services needed to perform control activities in the other country. With this conception, the SCCC requires very well established National Authorities, not only able to fulfill their responsibilities at a national level but also to support ABACC's activities (for instance, they need to expand their inspection capabilities to be able to provide ABACC with the necessary support to carry out inspection in the other country). This double role of the National Authorities is new in the safeguard's field. The technical support available from the two Parties embraces inspectors; consultants; equipment maintenance and calibration; preparation of standards, laboratory services and any other safeguards related study or service.

The SCCC consists of the General Procedures and the Application Manuals for each installation. The Application Manuals shall be negotiated between ABACC and the respective Country for each facility. The General Procedures contain the directives of SCCC. The adequate level of accounting and control of nuclear material, at each facility and other locations, shall be specified in the corresponding Application Manual taking into account the following parameters:

- the nuclear material category, considering its relevant isotopic composition;

- the conversion time;

- The inventory or annual throughput of nuclear material production.

The nuclear material accountancy shall be based on measurement systems compatible with the latest international standards and conforming to the SCCC objective.

ABACC is applying the criteria and procedures as needed to define the specific technical safeguard measures to be applied to a particular facility. The safeguards basic criteria and procedures adopted by ABACC do not constitute a rigid set of rules. Each specific case is studied and control measures are established taking into account the facility and the characteristics of the nuclear installations in each country. This approach is possible because of the small number of facilities to be safeguarded in both countries and permits ABACC to introduce modifications easily whenever necessary and to incorporate new safeguard's technologies, at present in development, but that could produce a considerable impact by increasing the effectiveness of safeguards.

As the Quadripartite Agreement demands a close coordination between the IAEA and ABACC, which, while avoiding unnecessary duplication of efforts, shall allow each Agency to fulfill its responsibilities and to reach independent conclusions, coordination meetings have been made between the two Agencies at the planning level. With this objective the "Guidelines for the Coordination of Inspection Activities between the Agency and ABACC" were agreed and are being applied. For example some equipment, either for being already installed at the facilities or rarely used or very expensive, must be shared between the two Agencies.

Table I describes the present situation of facilities and other locations in both countries.

3. THE ABACC INSPECTORATE

The inspections are performed on a cross national basis; Argentine inspectors carry out inspections in Brazil and vice-versa. The list of ABACC inspectors must be approved by its Board Directorate (Commission) among those suggested by the Governments of Argentina and Brazil. These inspectors do not work permanently for ABACC but are convoked by the Secretariat whenever necessary. The team of inspectors consists of 73 persons, 34 being Argentineans and 39 Brazilians. Part of the inspectors work for the State System and part of them are experts from the nuclear area which allows ABACC to count in its inspector's team on individual inspectors who have more experience in a particular type of facility, due to his/her routine job, and they are preferably selected for inspections in that kind of facilities.

This is one of the main advantages of this system since the experts are familiarized with the type of facility to be inspected. The average level of relevant technical experience of the inspector's staff is around 8 years. Another advantage of this staff of inspectors is the great responsibility they accept and assume in performing inspections in the name of their country.

Each technical sector of ABACC takes care of training courses for the inspectors in a specific field. So training in measurement techniques and equipment operation, accountability activities, preparing inspection reports, data bank uses and workshops involving physical inventory verifications (PIV) for a particular type of facility are some of the formal training courses developed by ABACC.

From the practical experience obtained in implementing the SCCC and the ABACC, several aspects can be highlighted:

- As the inspection staff is formed not only by safeguards experts but also by experts on design and on operation of installations, the Secretariat designs generally an inspection team formed by a safeguard expert and an expert on the type of facility to be inspected. As a consequence, the verification that the facility is operating as declared initially by the operator is more effective.

- A facility operator who performs an inspection in the other country will understand better the difficulties of the safeguards implementation in this type of facility, and after the inspection will try to improve the safeguards elements in its facility (record and report systems, measurement systems, etc.). This feedback is significant to improve the application of the control system.

- The technical cooperation between the two countries encompasses several applications of nuclear energy. As a consequence, the people involved in the various applications are known by the other country. This fact is important to increase the confidence and the effectiveness of the control.

- As the inspectors do not work full time for the Secretariat of ABACC, the pre-inspection activities and the preparation of inspection reports are very important steps. The reports have to be detailed and completed in order to enable a follow-up of solution of discrepancies and anomalies and to guaranty the continuity of the knowledge of the situation. As a consequence, a considerable fraction of the inspection effort is expended at the ABACC Headquarters.

4. INSPECTION ACTIVITIES AT FUEL CYCLE FACILITIES

Using the inspection effort defined for each facility and taking into account the facility operational program, an annual general inspection program is prepared by the Operations area of ABACC. According to the type of facility, the following activities could be performed:

- Verification of physical inventory and of inventory changes through independent measurements;
- Reports and records examination;

- Confirmation of the absence of material borrowing;

- Application and use of containment and surveillance measures;

- Verification of the operator's measurement system;

- Discrepancies and/or anomalies follow-up;

- Preliminary material balance evaluation;

- Verification of design information as necessary.

After the inspection, the inspectors have to prepare the inspection report at ABACC Headquarters. While the inspection report is being prepared on a computer, the ABACC's inspection data bank is automatically up-dated.

The samples collected by the inspectors during the inspection are analyzed on a cross basis in laboratories in Argentina and Brazil. In order to constantly check the status of these laboratories, the ABACC Technical Support area keeps running an inter-comparison program.

The first evaluation of the inspection is made by the inspector in the field, and they try wherever possible to solve the pending problems immediately. The Planning and Evaluation Officers are responsible for the final evaluation and for preparing the notification of the inspection results to the State.

Table II presents the number and type of inspections that were carried out by ABACC in the last three years, in compliance with their objectives. In order to study the impact of the safeguards activities on the facility operation, it is important to observe the inspection effort for some relevant installations. As examples considered in this paper, one considers the fuel fabrication plant in Argentina (CONUAR) and the centrifuge enrichment plant in Brazil (LEI). In CONUAR, ABACC normally performs one PIV and 3 interim inspections per year with a total inspection effort of 21 PDI.

LEI is a small centrifuge enrichment plant, whose safeguards approach is complex, essentially due to the verification that the facility is operating as declared. In order to verify the inventory and internal and external flow of material, ABACC is performing one PIV and 5 interim inspections per year. Additionally, ABACC performs 3 unannounced inspection per year. The total inspection effort amounts to approximately 30 PDI.

TABLE I. FACILITIES AND LOFs IN ARGENTINA AND BRAZIL

Type	Argentina	Brazil	Total
Conversion facilities	7	1	8
Enrichment facilities	1	2	3
Fuel fabrication facilities	3	1	4
Power reactors	2	1	3
Research reactors	6	3	9
R&D facilities	1	3	4
Critical/sub critical units	-	3	3
Storage facilities	3	2	5
LOFs on fuel research	3	5	8
LOFs on reprocessing research	-	1	1
LOFs analytical lab.	3	2	5
Other LOFs	8	6	14
total	37	30	67

TABLE II.   ABACC'S INSPECTIONS

Inspections	1994	1995	1996
DIQ Verification	73	5	8
PIV and interim verifications	113	139	151
Total Inspection Number	186	144	159
Inspection Efforts (B) (PDI)	562	683	626
Inspectors Availability (C) (person-day)	1506	1489	1411
C/B	2.7	2.2	2.3

The main direct inspection costs are: travel (air fare, per diem, and associated expenses); salaries of inspectors while on duty travel and for performing inspection-related duties at ABACC Headquarters (This cost is covered directly by the Countries); destructive analysis of samples taken during the inspections, including the transport costs; NDA equipment, including maintenance and spare parts; Containment and surveillance equipment, including spare parts and maintenance, production and verification of seals, associated duty travel and staff salaries. In addition, one shall consider all costs connected with the inspection efforts, i.e. management, negotiations, data processing, evaluations, etc. Currently, ABACC has 10 staff members in the professional category, 2 administrative officers and 7 staff members in the service category.

5. IMPACT OF THE CURRENT SAFEGUARDS ACTIVITIES ON THE FACILITY OPERATION

5.1. The Brazilian point of view

Before the SCCC implementation, Brazil had 2 safeguards agreements: INFCIRC/110 (Brazil-IAEA-USA) and INFCIRC/237 (Brazil-IAEA-Germany). Both follow the guidelines of the old safeguards system (INFCIRC/66.Rev2). Nuclear material should be submitted to safeguards, if it is being or has been: supplied under the agreement(s), produced, processed or used in a facility that has been supplied under the agreement(s), or produced in or by use of safeguarded nuclear material.

When the SCCC began to be implemented, several changes occurred. All the nuclear material in the country came under the control of this system, provided it had the composition and purity suitable for fuel fabrication or for isotopic enrichment. Consequently, there was an increase in the work demand. All the facilities submitted the Design Information Questionnaire (DIQ) to ABACC. The facilities already under safeguards of the old agreement reviewed and updated the information adapting to the new DIQ format, and the other facilities had to prepare a new document.

A new reporting system was adapted using the documents Inventory Change Report (ICR), Material Balance Report (MBR) and Physical Inventory Listing (PIL). The accounting records had to be modified to comply with the new rules and conventions of completing the updated reports. As a result, it was necessary for the National Authority to develop a standard General Ledger for all nuclear facilities, to comply with the reporting system, in addition to allowing to sent the reports to ABACC through information technology.

Significant efforts were made in order to optimize, standardize and automate the accounting systems, of Brazilian nuclear facilities. The nuclear facility operator training, has successfully been aimed at implementing a unified system. This made it possible for the National Authority to have efficient control and fulfill deadlines agreed upon by ABACC and the Agency regarding the presentation of accounting reports.

The Initial Physical Inventory Taking (PIT) of all nuclear facilities was established. Subsequently, inspections of Physical Inventory Verification were carried out by ABACC. There was a need for the facilities to establish or to improve a system of measurements to determine the quantities in the inventory of nuclear material and the variations for each material balance area.

Regarding the notifications of exports, imports and transfers between Argentina and Brazil, new rules have been established in the SCCC and in the Quadripartite Agreement, obliging the facilities to send Annual Operational Programs to both agencies. The date that the physical inventory is to take place must be stipulated and communicated. Because of all the new measures of the SCCC, both the Brazilian National Authority and the facility operator have had to increase man power in order to carry out all the commitments.

A Case Example: The Uranium Enrichment Plant in Brazil

In the development of the nuclear fuel cycle, Brazil has opted for the uranium enrichment centrifugation method. The process of research and development has been carried out by the Brazilian Nuclear Energy Commission (CNEN) and the Brazilian Navy since the early 80's. The Isotopic Enrichment Laboratory - LEI, began to operate in 1987 for testing centrifuges in cascade mode. The laboratory has three small cascades operating independently with a reduced inventory of about 0.2 significant quantity. In 1989 the enrichment laboratories came under the National Safeguards control. The national inspections are carried out by the Safeguards Division of CNEN.

Before the creation of ABACC, a group of Argentinean and Brazilian experts from the enrichment and safeguards areas, was created to develop a safeguards approach for enrichment facilities in both countries. A preliminary project of nuclear material control for LEI was prepared taking into account the technological and commercial secrets involved. The separative work capacity of each centrifuge and its physical and structural aspects are considered to be secret. Consequently, the cascades are surrounded by panels to avoid the machines being observed. In addition to this, inspectors are not permitted to identify the cylinders connected to the feed and withdraw stations, as this data would allow to determine the centrifuge separative work capacity. When ABACC started its operation, the group of experts was designated group of consultants of ABACC.

LEI constitutes one Material Balance Area (MBA); during the PIT the process operation is interrupted and all nuclear material transferred to the storage area. The feed cylinders cannot be connected to the process before they are made available for verification; the product and tails cylinders cannot be shipped out or blended before they are made available for verification. ABACC verifies the operator total uranium and U-235 mass balance. As the operator considers the individual cascade capacity a sensitive information, the mass balance is evaluated for the whole laboratory. ABACC performs 4 to 6 interim inspection per year. During the interim inspections, ABACC will verify the flow of nuclear material. The operator undertakes to present during the interim inspection for ABACC verification (i) the UF_6 that will feed the facility during the time until the next inspection, and the UF_6 product and tail produced since the last inspection. So the operator prepares a kind of buffer, i. e. a temporary UF_6 storage of all material processed or to be processed in the facility in the period between two inspections (in general two or three months). These activities will be supported by a C/S System, that confirms that only verified feed cylinders are connected to the F/W stations. Further, ABACC considers a frequency of three non-announced inspections (LFUA type) per year to the cascade's area to verify that there are no additional feed or takeoff points inside the cascade area, no UF_6 containers are present and no connections between the cascades. The inspector's access may be delayed not more than 2 hours after official request for it. When the Quadripartite Agreement (INFCIRC/435) entered into force, the IAEA adopted the same methodology as ad-hoc procedures. Currently a safeguards approach for LEI is being negotiated between ABACC, the IAEA and Brazil, the main difficulty being the scenario of accumulation of nuclear material behind the panels. Alternatives of control are being studied such as a perimeter control approach and the development of non-destructive measurement for detecting nuclear material behind the panels. In the framework of Program 93+2, Part 1, the Agency performs periodically environmental sampling at LEI.

5.2. The Argentinean point of view

A case example: The Fuel Fabrication Plant

The fuel cycle in Argentina has been designed to cover the requirements of the On-Load Nuclear Power Plants using natural or 0.85% enriched uranium fuel elements. The CONUAR S.A. Fuel Element Fabrication Plant with its three fabrication lines (Atucha type natural and enriched uranium fuel elements, and natural uranium Candu type), is where the whole line of fuel elements

225

required by Atucha and Embalse Nuclear Power Plants is fabricated, using as raw material the uranium oxide produced at Cordoba's Conversion Plant.

CONUAR is located at the Ezeiza Atomic Centre, in the outskirts of Buenos Aires; the Atucha-I Nuclear Power Plant (NPP) is located in Lima about 100 km from Buenos Aires; the Embalse NPP and Córdoba Conversion Plant are located in different points of the Córdoba Province, at a distance of 800 km from CONUAR. From a point of view of safeguard's application, these installations are very narrowly related. In the Candu Reactor, fuel elements imported by CONUAR are also being used.

In the Southern part of the country, at a distance of 2000 km from Buenos Aires, the Uranium Hexafluoride Conversion Plant is located, that uses as raw material UO_2 natural powder. For this reason it is entailed to CONUAR.

In CONUAR all metallurgical processes required for obtaining the oxide uranium sintered pellets and the fuel elements assembling are performed. In the particular case of Atucha's fabrication line, as long as the new Atucha type fuel fabrication with enriched uranium is not completed, it is working alternatively with natural and enriched uranium at 0,85%, depending on the requirements.

Safeguards approach and implementation experience

For the nuclear material control, CONUAR works as one material balance area, in which an annual Physical Inventory Verification (PIV) inspection is performed. Interim inspections for the verification of inventory changes are also performed. The pellet loading station is controlled to detect the diversion of nuclear materials into the MUF through the evaluation of the material balance equation.

Likewise, to cover the scenario of material borrowing, simultaneous random inspections to the UO_2 powder storage in the fuel element fabrication plant are performed, due to the PIV in the Cordoba Conversion Plant or in the UF_6 Conversion Plant at the Pilcaniyeu Complex, or to the fuel elements storage, due to the PIV in the NPP's. During the PIV in CONUAR, simultaneous inspections in some of the above mentioned facilities are foreseen.

From the operator's and National Authority's point of view, the safeguards application implies to take the necessary and appropriated control measures to minimize the impact in the facility's normal operation. Particularly in relation with the PIV inspections, the following has been observed:

a) The need to interrupt production;

b) Some materials are not fully accessible for verification;

c) Lost of Quality Assurance of items selected for verification (fuel elements already assembled); and

d) Large number of national inspectors is necessary for the simultaneous inspection of the Fuel Fabrication Plant and others in order to satisfy the borrowing criteria.

The interim inspections for the verification of national and international transfers, of other inventory changes and of other strategic points have also an impact on the facility's operation and appropriated actions are required to minimize it. In general, the following must be considered:

a) The need of advanced notification;

b) The eventual lost of Quality Assurance of the fuel elements;

c) Compatible criteria of the international control organizations (ABACC, IAEA) to perform the verifications; and

d) Difficulties on the verification of the pellet loading station for operative reasons.

To minimize the impact of the facility shutdown and the partially accessible material, the physical inventory taking (PIT) is performed together with the National Authority, starting with the homogenization, pressing and sintering sectors. These are under normal operational conditions, since previously the UO_2 amounts required to keep them functioning are reserved and the rest of the installation is shutdown. The activity starts with the records audit and goes on with the inventory taking of the UO_2 powder, of fuel elements ready for transfer, of fuel rods, and of pellets at loading stations. The PIT ends in the press, homogenization and sintered zones, whose operation is finally interrupted until the verification by the IAEA and ABACC are performed. The inventory so established and the information from the homogenization operational records allow to estimate the amount of material partially accessible and the Material Unaccounted For (MUF) of the facility. If the values result unusually high and exceed the acceptable limits for a PIV, the National Authority requires the homogenization's total discharge, although such operation will considerably delay the Plant re-start. The ABACC's and IAEA's verifications start in this area and follow an inverse course in order to liberate the plant as soon as possible.

The verification of fuel elements contained in shipping containers requires the opening of some boxes and the handling of fuels for identification and measurements. In this occasion the quality assurance granted by the manufacturer could be lost. This is especially conflictive in the case of imported fuel. In this case, the nuclear material verification (with the present methods) could produce a prejudice to the fuel fabrication plant in case of an eventual posterior rejection by the installation.

The simultaneous inspections to cover the scenario of the nuclear material borrowing result practically in short-notice inspections, with approximately 12-hours notice for distant facilities. This requires a fast logistic co-ordination and the availability of national inspectors.

In relation with the verification of domestic transfers, the methodology applied by the IAEA requires the presentation of a detailed operational program with the dates on shippings and receipts to allow the planning of such inspections. Usually, such a program is not available within the previously required time and, besides that, for contractual reasons, last time changes are very frequent. This forces a permanent program updating, but under some circumstances it is not possible to notify in advance as required (~4 days).

To validate the verification of the shipment at the conversion plant as well as the receipt at the fuel fabrication plant, the IAEA seals the containers at the shipping facility and verifies the seals at the receiver facility. If a container seal is broken during the transport, the IAEA verifies 100% of the material contained in this container and verifies the rest of the population with an average detection probability for gross and partial defect for natural uranium, or with an average detection probability for gross, partial and bias defect for enriched uranium.

In the case of fuel element transfers, due to the Quality Assurance reasons before mentioned, the shipping cask is sealed at the shipping facility and the fuel elements are verified at the NPP with an average detection probability for gross defect for natural uranium, and with an average probability for gross and partial defect for low enriched uranium. Since the IAEA current criteria do not require the verification of fuel element receipts at OLRs, this practice normally generates an additional safeguards activity in the NPPs.

The nuclear material involved in domestic transfers is verified with another methodology by ABACC. During the PIV and interim inspections, ABACC verifies the material received since the previous inspection and the material expected to be transferred until the next inspection. Although this methodology is appropriate for the stratum of UO_2 powder and fuel elements of the Atucha type, the Candu fabrication line works with a very small accessible stock material. For this reason, to verify the stock could be necessary to open the boxes with the consequent eventual loss of Quality Assurance and the generation of additional costs. A similar problem occurs with imported materials.

The differences between the two organizations in the verification of transfers introduce problems in the co-ordination of inspections and, in some cases, two different inspections are performed simultaneously in the same facility.

In some interim inspections pellet sampling is performed at the pellet loading station. As the Atucha line alternates campaigns of natural and enriched uranium, the verification of this strategic point requires an appropriate planning from the control organizations and a periodic updating of the operative program.

Proposed Solutions

To decrease the impact of inspections due to the borrowing scenario, the National Authority has recommended the simultaneous PIT in all conversion and fabrication facilities. Simultaneous inspections to the NPPs are also foreseen, when the fresh fuel inventory is higher than a significant quantity. This procedure has been applied for the second consecutive year and it diminished the interference with the plant's operation, has improved the co-ordination between control organizations and has allowed to rationalize costs for the National System of Accounting for and Control of Nuclear Materials.

The problems related to quality assurance of national or imported packaged fuel that has to be verified have been temporarily solved by the application of seal in CONUAR and the posterior verification at the NPP. A final solution to this problem that should contemplate the operational constraints of the facility and the PIV's requirements, needs the implementation of non-destructive methods for the verification of material contained in a transport container and the modification of the present safeguards criteria.

The problems related to the verification of domestic transfers and the possible solutions are still being studied. The goal is to minimize the need of advance notifications, to optimize the inspection's effort associated with these verifications, to improve the co-ordination between ABACC and the IAEA and, fundamentally, to minimize intrusive practices in the facility operation.

It shall be mentioned that the inspection effort to the initial part of the nuclear fuel cycle in Argentina is significant. The new safeguards measures should allow more efficiency in safeguards application without decreasing, rather incrementing, its effectiveness. For this objective it seems to be important to revise the safeguards approaches and criteria for the facilities involved, as well as strengthening measures, including other measurement methods.

6.   CONCLUSIONS

ABACC is applying its safeguards system in a way to balance conveniently the safeguards effort depending on the relevancy of the concerned nuclear activity.

In principle, the regional system may contribute in many ways to enhance the safeguards, which can be summarized as follow:

- The model of regional organization can reduce strongly the costs involved in safeguards implementation; ABACC, for instance, has a permanent technical staff of only 10 people that have a coordination function, and may use conveniently the technical and human resources of the countries;

- The regional organization controls a small universe of facilities and materials and is not constrained by requirements of universality of procedures, as required in multilateral systems. It is therefore in better condition to maximize the verification procedures on those stages in the nuclear fuel cycle involving the production, processing, use or storage of nuclear material from which nuclear weapons could readily be made.

- The safeguards criteria and procedure can be applied to each specific facility, since the number of nuclear facilities is not too large and allows for a substantial increase of the efficiency and effectiveness of safeguards. For instance, there is no basic constraint for the definition of significant quantities or detection time;

- The mutual inspection model, as implemented by ABACC, allows to use the best available expertise in both countries. This makes it possible to perform in each inspection the re-verification of the technical characteristic of installations and therefore to improve the effectiveness of safeguards.

From the Brazilian and Argentinean points of view expressed in this paper it may be concluded that the implementation of the Bilateral and Quadripartite Agreements represented a considerable impact on the work load of the National Authorities and operators. To optimize the implementation of safeguards a close coordination between ABACC and the IAEA is required. While avoiding unnecessary duplication of efforts, each organization should be allowed to reach independent conclusions. For this purpose, ABACC and the IAEA should work jointly, whenever feasible, according to compatible safeguards criteria of the two Organizations.

Considering the short time of implementation of the Quadripartite Agreement (3 years) and the first results of the cooperation between ABACC and the IAEA which are reflected in the agreed "Guidelines for the Coordination of Routine and Ad-hoc Inspections" between the Agency and ABACC, further improvement in the relationship of the two agencies is expected in the future.

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NON-PROLIFERATION AND SAFEGUARDS ASPECTS
OF ALTERNATIVE FUEL CYCLE CONCEPTS*

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Abstract

Timely visibility on the development, evaluation and optimization of fuel cycle concepts with respect to nonproliferation characteristics should be emphasized in the early stage of planning a civilian nuclear power program, by fuel cycle developers, reviewers and decision makers. Fuel cycle technologies have inherently differing levels of nonproliferation characteristic profiles. Institutional and/or multi-national arrangements have been effective in reducing the nonproliferation concerns. The implementation of international safeguards further reduces these concerns by the timely detection of a possible physical diversion of SNM from fuel cycle facilities. Fuel cycles are safeguardable, but the nonproliferation characteristics of fuel cycle concepts differ significantly with consequent impacts on the international level of technical safeguards measures. The paper comments on characteristics of some of the fuel cycle concepts for the purpose of exploring the need to develop advanced nonproliferation and safeguards measures.

1. INTRODUCTION

The international commercial deployment of nuclear fuel cycle systems for electricity generation has essentially followed the evolutionary extension of the consensus arrived at in the 1980 INFCE study [1]. The technical study focused on the importance of preventing nuclear proliferation by the misuse of fuel cycle technologies, facilities, and materials for the purpose of developing nuclear weapons. Several countries have proposed the recycling of spent fuel without the separation of plutonium from uranium and fission products. The concepts are alternatives to either direct long-term storage or the Purex reprocessing of spent fuels.

Some of the fuel cycles being investigated include the dry-recycle processes such as the direct use of reconfigured PWR spent fuel assemblies into CANDU reactors (DUPIC), and the low-decontamination, single-cycle co-extraction of the fast reactor fuels in a wet-Purex type of reprocessing. The nonproliferation advantages usually associated with these non-separation processes are:

- The highly radioactive spent fuel presents a barrier to the physical diversion of the nuclear material from the fuel cycle;

- The need to dissolve and chemically separate the plutonium from the uranium and fission products; and

- The spent fuel isotopic quality of the plutonium vector is further degraded.

Although high radiation levels and the need for reprocessing may be perceived as a barrier to terrorists or other subnational groups, international proliferation concerns are addressed primarily by the material accountancy and verification activities which are the international safeguards measures of fundamental importance, with containment and surveillance as important complementary measures.

Consequently, the non-separation fuel cycle concepts have to be evaluated on the basis of the impact that the fuel cycle processes may have on nuclear materials accountancy. Safeguards R & D would have to address the implementation of advanced non-destructive assay and accountancy methods for dry-processing systems having concept specific holdup characteristics (measurable and non-measurable).

The purposes of this paper are:

● To profile the proliferation characteristics of some of the fuel cycles concepts

● To suggest that the nonproliferation concerns be introduced into the early stages of a development program; and

● To perhaps aid in the more effective implementation of international nonproliferation initiatives and safeguards methods.

2.   CANDU / PWR CYCLE

The residual reactivity in the spent fuel of a PWR cycle can be used to extend the fuel burnup capability in the high neutron economy of heavy water reactors. The direct use of spent PWR fuel in CANDU reactors (DUPIC) has the potential of reducing the natural uranium resource requirements, and of reducing the overall spent fuel arisings by refabricating spent PWR fuel into CANDU reactor fuel bundles for power generation [2,3].

The DUPIC fuel cycle concept utilizes dry-bulk-processing techniques. The dry process involves the mechanical dismantling, segmenting, and decladding of the PWR fuel elements, and the grinding of the U/PuO_2 spent fuel into powder. The spent fuel oxide powder is then subjected to cycles of oxidation/reduction processes, sintered into pellets and configured into CANDU fuel bundles. The process removes a high fraction of gaseous and volatile fission products. The remaining fission products with high gamma and neutron radiation levels necessitate that refabrication and fuel assembly handling be shielded and automated.

Although the gamma radiation and neutron emission levels could be perceived as a layered barrier to deter subnational theft or diversion, the radioactivity does not present a layered barrier to the national diversion and the international level of proliferation concerns. The proliferation resistance characteristics address the barriers to accessing the material, and the barriers to converting the nuclear material for uses other than for power generation. International proliferation concerns require that stringent safeguards in nuclear material accountancy and validation be implemented throughout the dry-bulk process. The radiation barriers could compromise the efficacy of the accountancy and validation measures.

In the dry-bulk process, the nuclear material forms, inventory, and flow are such that current nondestructive assay (NDA) methods may be limited. Research and development would have to address specific measurement methods and validation standards to directly assay the nuclear materials in the two major waste streams from the mechanical dismantling, segmenting, and decladding processes of PWR fuel assemblies and from the oxidation/reduction, sintering/pelletizing processes. Dry-bulk powder processes have characteristically high holdup inventories and excessive nuclear material holdup could be expected in the DUPIC dry-bulk-processing plant.

With respect to barriers in converting the nuclear material to non-fuel uses, the softer neutron spectrum in the CANDU reactors generates a plutonium isotopic vector with greater concentrations of the even plutonium isotopes (Pu-240 and -242) than in the initial PWR spent fuel feed. The fresh fuel DUPIC plutonium isotopic composition for a 35GWD/T PWR power operation, is transmuted into a plutonium isotopic composition for a 16GWD/T DUPIC once-through power cycle, as listed in Table I. This results in increased specific neutron emission rates by factors of two or more than in the initial PWR or CANDU spent fuel arisings, maintaining the plutonium more unattractive for non-fuel uses.

TABLE I. DUPIC PU ISOTOPIC COMPOSITION (W/O)

Isotope	Fresh Fuel (35GWD/T)	Once-Through (16 GWD/T)
238	0	0
239	60	38
240	26.6	42.7
241	8.35	6.68
242	4.48	12.2

The advantages of the DUPIC cycle are outlined as follows:

• No wet-processing is required

• The geological disposal requirements of the spent PWR and CANDU fuels are greatly reduced; and

• The natural uranium requirements for the CANDU phase of the fuel cycle would also be greatly reduced.

The early stages of a feasibility exploration program would have to include early design considerations which address the following:

• Proliferation characteristics based on the radiation levels of the fuel assemblies as being within a subnational level threat or an international level of proliferation concern;

• Geologic repositories would still be needed for the once-through DUPIC fuel assemblies; and

• The impact on the IAEA materials accountability measurement methods for establishing dry-process holdup and recoverability of the plutonium/uranium mixture.

3. FAST REACTOR SINGLE-CYCLE CO-EXTRACTION

The fast-reactor advanced-fuel-recycle concept is based on the characteristic neutron energy spectra of fast reactors [4]. The complete separation of plutonium and uranium is a sufficient condition for fast reactor power systems, but is not necessary. Since the fast reactor fuel cycles are capable of operating with a high concentration of nuclear material impurities, there is a reduced need for the purification cycles beyond the initial co-extraction stage of the Purex wet-separation process. Decontamination factors of 10^3 or less are acceptable in the fast reactor fuel cycle for power generation. The Pu/U/fission product stream retains the radiation barrier to the subnational theft or diversion. The fast reactor single-cycle co-extraction concept has many of the attributes outlined in the dry-cycle process. However, the coprocessing and the fabrication aspects of the concept address only the subnational level of proliferation. The elimination of the purification stages greatly reduces the size of the conventional Purex process. The integration of reprocessing and fabrication processes into a single unit fuel cycle plant would reduce the nonproliferation concerns by the contraction of the transportation links between the fuel cycle facilities.

The international aspect of nonproliferation concerns must depend on direct nuclear materials accounting, validation and verification measures. International safeguards R & D should address the development of accountancy techniques to measure directly the plutonium inventories and flows in the severe gamma and neutron radiation fields of the fission products.

In general, fast reactor fuel management should address separately the core nuclear materials and the blanket materials. Spent radial blanket assemblies contain weapons-grade plutonium, and consequently, nonproliferation concerns suggest that the blending of the radial blanket materials with core materials be completed as far upstream as possible for the conventional (blanketed) fast reactor power cycle. The moderate (non-radial blanket) plutonium burner operations does reduce the plutonium isotopic quality compared to the conventional operating mode. In the integral fuel element design, the axial upper and lower blanket sections and the core sections are mechanically separated and simultaneously dissolved in the dissolution tank.

Although co-extraction may mitigate international proliferation concerns compared to existing conventional fast-reactor fuel cycles, safeguards methods must be developed to minimize fuel handling and processing operations for spent blanket assemblies in and out of the reactor environment.

The inaccessibility of co-extracted fuel Pu/U/ fission product streams (dry-bulk or single-cycle) is not necessarily to be construed as a lesser proliferation concern. The radioactivity will decay over 30 to 100 or more years to a level where it no longer deters subnational threats. International safeguards measures designed for this phase of the fuel cycle should ensure irreversibility. The high mass throughput of fissile material in the fast reactor cycle requires emphasizing containment and surveillance methods.

4. THORIUM - URANIUM FUEL CYCLES

The thorium-uranium fuel cycle is being pursued on a limited scale by several countries. The primary incentive for the thorium-uranium fuel cycle would be to utilize indigenous nuclear material resources in conventional commercial thermal and fast reactor power systems. The exploitation of thorium resources is essentially a long-term, large-scale energy-generation option [5,6].

The denatured uranium (i.e. low enrichments in U-235 or U-233) fuel cycle systems should be assessed in the context of established international proliferation criteria. The U-233 produced in the Th-U cycle is as fissionable and perhaps as radiotoxic as Pu-239. Although systems have been proposed in which U-233 is denatured with U-238, even the denatured Th-U/U-233 introduces nonproliferation concerns. The suggested cycles include U-233/U enrichment levels ranging from three to twelve percent or more.

The thorium-uranium fuel cycles have certain nuclear characteristic features which persist through all stages of the fuel cycle process and consequently may strongly influence the design of IAEA safeguards.

Two fundamental invariant characteristics in the denatured uranium-thorium fuel cycle are:

1. Chemical reprocessing is a necessary phase of the fuel cycle, and

2. The U-233 and the plutonium isotopes are in combination throughout the back end of the cycle.

(1) The separation of the uranium-thorium and plutonium is necessary for reactor systems in a symbiotic power complex operating at high conversion ratios with only denatured uranium being used in the front end of the cycle. The assessment of the impact on safeguards considerations should include the following:

a) The fissile isotope identification, materials balance, and accountability will involve U-233, significant concentrations of plutonium and, depending on the total reactor deployment strategy, U-235;

b)　　Safeguarding techniques should be introduced for continuous surveillance and mass flow accountability of the plutonium streams, and safeguarding the reconfiguration and casting of the separated plutonium for storage (retrievable and nonretrievable) and the consequent long-term safeguarding of the storage facilities.

(2)　　In consideration (a), the spent fuel of the denatured U-233/U-238/Th cycle contains significant amounts of plutonium (about one-fourth to one-third) of the plutonium content in the spent fuel of the uranium/plutonium fuel cycle. The safeguards concerns between these two cycles are therefore of equal significance. However, an added safeguards problem arises in that discharged denatured fuel contains a significant amount of U-233, and the fissile accountability must now be applied to the uranium, thorium, and plutonium process streams through all phases of the fuel cycle. On the international level of safeguards concern, gas-centrifuge enrichment technologies and the electromagnetic isotopic separation technology (EMIS) calutrons make the isotopic separation of the denatured uranium enrichment levels a relatively low-level effort. The safeguards concerns would have to be emphasized at the front-end of the denatured fuel cycle.

Studies in isotopic separation processes (electromagnetic isotope separations) have indicated that the separation of U-233 is greatly facilitated in comparison to the isotopic separation of U-235 in the low enrichment U-235/U cycle [7]. Estimates indicate that the effort level to enrich U-233/U fuels can be lowered by factors of 3 to 20 in comparison to the re-enrichment of 3% U-235/U. The ease of the isotopic separation is a consequence of the mass difference of five between U-233 and U-238 as compared to three for the U-235 and U-238, the higher concentration levels of the U-233/U fuel, and the lowered inventory fuel requirements to achieve significant-quantity mass levels. These considerations would have to be integrated into the evaluation of the nonproliferation characteristics of the thorium/uranium cycles.

The anticipated impacts on safeguards of the thorium-uranium fuel cycles are speculative, since sustaining fuel management strategies have not yet been detailed. The source of the U-233 for startup, the disposition of the plutonium generated in the denatured fuels because of the presence of U-238, and the precise composition of the U-233/U fuel should be evaluated as the fuel cycles are developed further. The safeguards assessment of the U-233/U/Th fuel cycles would involve the layout of symbiotic systems to establish the somewhat unique aspects of the fuel:

- Feed sources of U-233 would be necessary since the denatured cycles may not be self-sufficient in flow and inventory of fissile material;

- The impact on safeguards relating to the differences in the enrichment properties and capacity requirements between U-233 and U-235; and

- The impact on IAEA safeguards methods resulting from the radioactivity of the daughter products of the U-232;

- Proliferation concerns be addressed at the front-end of the fuel cycle.

The safeguards problems introduced into the nuclear material accountability methods by the denatured thorium-uranium cycle will require research and development programs in implementing advanced chemical analytical measures and NDA techniques.

5. EXCESS PLUTONIUM DISPOSITION CYCLES

The disposition of excess weapons plutonium from disarmament programs has been explored in many studies and by many countries in the past few years. There appears to be a general consensus and commitment for the continued study of two major options: use in reactors, and immobilization [8]. The reactor alternative involves the use of MOX fuel as a fuel source for commercial reactors (LWR's, WWER's, CANDU's, and Fast Reactors) [9-11]. The immobilization alternative involves the vitrification of plutonium in a matrix log inserted within a canister containing radioactive material (can-in-canister). The consensus also included the time lines: the plutonium disposition program is to be initiated in approximately 10 years, and the program should be completed in 25 to 30 years thereafter.

5.1. Thermal reactor fuel cycle (LWR, WWER)

In the case of the MOX fuel burning in thermal reactors, the once-through fuel cycle operation degrades the weapons-grade plutonium into a form that is as unattractive and inaccessible for weapons use as that of plutonium contained in the spent fuel from current commercial reactors (Spent Fuel Standard) as listed in Table II.

TABLE II. NOMINAL PLUTONIUM ISOTOPIC COMPOSITION (W/O)

Pu-Isotopes	Weapons Grade	LWR, Spent Fuel Standard (33-36 GWD/T)	LWR,WWER, MOX Once-through (40-45 GWD/T)	Fast Reactor Once-through (100 GWD/T)	CANDU Once-through (10 GWD/T)	CANDU Inert Matrix Once-through (733 GWD/T)
Pu-238	0.01	2	0	0.1	0.0	0.0
Pu-239	93.6	55	52	85.5	51.6	14
Pu-240	5.9	26	29	13.2	37.9	46
Pu-241	1.4	10	15	1.1	8.5	20
Pu-242	0.1	7	4	0.1	2.6	20

The specific neutron emission rate from the even-plutonium isotopes, "equivalent" to Pu-240, is expected to be comparable for the reference spent fuel standard (SFS) and the once-through fuel cycle of the LWR/WWER MOX loading. The "Pu-240 equivalence" defines the weighted neutron emission rates of the even-plutonium isotopes.

5.2. Fast reactor fuel cycle

The burning of weapons plutonium or MOX in fast reactors with conversion ratios of less than unity, results in a plutonium composition vector, for the once-through cycle (open cycle), as listed in the last column of Table II. The isotopic degradation does not differ much from the initial weapons-grade plutonium. For the higher grade weapons-plutonium, the degradation of the plutonium isotopic vector in the fast reactor spectrum can be expected to differ even less [10]. The plutonium isotopes approach the LWR spent fuel standard concentration levels, if an equilibrium feed and discharge fuel recycle mode of operation is utilized in the fast fuel cycle However, the equilibrated fuel cycles would require higher burnups equivalent to some 4 to 5 recycles which would then exceed the time line for completing the disposition program.

5.3.   CANDU reactor fuel cycle

The Atomic Energy of Canada Limited (AECL) has proposed options for using excess weapons-plutonium in the CANDU reactor system [12,13]. The CANDU reactor fuel cycles have a characteristic well-thermalized neutron spectra, with a high neutron economy resulting in higher concentration levels of the even-plutonium isotopics (i.e. Pu-240/242) than in the fast-reactor spectra. The AECL studies indicate that the weapons-grade plutonium MOX fuel can be introduced into the CANDU reactor fuel cycles as a full MOX core in a once-through mode. The plutonium isotopic composition of the CANDU spent MOX fuel is listed in Table II, for burnups of about 10GWD/T. The specific neutron emission rate approaches the LWR MOX option and the LWR spent fuel standard (SFS). The neutron emission rates correspond to the "Pu-240 equivalence" isotopic concentration of 43, 34, and 49 by w/o in the CANDU, LWR-MOX, and the LWR-SFS options, respectively.

The AECL studies included the alternative option of introducing weapons-grade plutonium in an inert-matrix (non-fertile) fuel material. With anticipated long burnups of 733 GWD/T, the plutonium content was reduced by 80% of the fresh fuel. The resultant spent fuel plutonium isotopics vector is listed in Table II. The "Pu-240 equivalence" for neutron emission rates is 86 percent, which is almost a factor 2 greater than in the spent fuel plutonium of the CANDU- and the LWR-MOX options, and the LWR-SFS.

5.4. Safeguards measures

The need for advanced safeguards development in direct plutonium accountability measures exists in all of the proposed disposition options. NDA and DA systems development for the dry-bulk processes should be advanced:

- To enhance the transparency of the weapons-plutonium flows and inventories

- To improve material accountability

- To directly establish isotopic compositions, and

- To ensure that the weapons material are indeed unattractive and inaccessible, and irreversible, for uses other than the nuclear power fuel cycle.

6.   SUMMARY

Fuel cycle technologies have inherently differing levels of proliferation characteristic profiles. Institutional and/or multi-national arrangements have been effective in reducing proliferation concerns. The implementation of international safeguards further reduces proliferation concerns by allowing the timely detection of a diversion of SNM from fuel cycle facilities. The proliferation characteristics of different fuel cycles could differ significantly, with consequent impacts on the required level of technical safeguards measures. The nonproliferation considerations should include:

- Generation/disposition of fissile materials

- Development of high burnup fuels

- Transparency of fissile material flows and inventories

- Balancing supply and demand of fissile materials, and

- International safeguards and institutional arrangements.

Advanced NDA and DA methods for direct plutonium accountability, being developed in many analytical chemistry laboratories, should be explored for implementation on an engineering scale in on-line processing operations.

The reduction of radioactive hazards has both short- and long-term concerns. Hazards-analysis addresses the consequence of exposure, whereas risk analyses requires the modeling of radionuclide dispersion and intrusion into the biosphere. These two analyses are expected to impact differently on the site selection and design of the geologic repositories. Waste repositories will be needed for all fuel cycle concepts and consequently should be a continuing development program. Fuel cycle developments should include waste management as an integral phase of the concept. Institutional and/or regional consortia involving fuel cycle options and fuel cycle services will be influenced by the long-term nonproliferation and health hazards concerns as well as the utilization of nuclear energy resources.

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SESSION VI

GUIDELINES FOR THE RESPONSIBLE MANAGEMENT OF PLUTONIUM

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Abstract

Since 1994 an informal group of representatives of States party to the NPT has been trying to develop agreed international guidelines for the responsible management of non-military plutonium. This paper gives a brief description of the outcome. Since the results are still subject to decision by Governments, the description must be in general terms only. The paper describes the background to, and genesis of, the discussions and the general approach taken, which was based on commitment to the NPT, national responsibility for the management of nuclear materials and the fuel cycle, upholding of the IAEA=s safeguards system, and a focus on civil material. An indication is given of the development of the Group=s thinking, especially the decisions that any guidelines must be capable of accommodating surplus military plutonium, as well as civil, and that the main focus should be on measures to increase transparency. The resulting guidelines are described. Their main features are a re-statement of commitments and standards for the management of non-military plutonium with regard to non-proliferation, safety, and other fields, a commitment to the management of such plutonium according to a consistent national strategy, and a commitment to the publication of information on that strategy, and of annual statistics for holdings of plutonium in a consistent format. Other aspects of the guidelines are also explained. Finally, an attempt is made to assess the possible practical effects of the guidelines if adopted by governments.

1. INTRODUCTION

My aim today is to describe the results of an attempt to formulate agreed international guidelines for the management of non-military plutonium. This work was carried out over the last three years by an informal group, over which I had the honour to preside, drawn from a group of States Parties to the NPT who are the main holders or users of separated plutonium.

The text which I shall describe has been agreed ad referendum; not all the Governments concerned have yet taken a formal decision on it - and when they do so, promulgation will be for them. It will therefore be understood that I am not in a position to go beyond a description of the results of the discussions or make available the text itself. It is not usual, indeed, to make a presentation at such a stage but the participants in the discussions have agreed that I should do so, in the hope that a record of our objectives and the approach we took will be a contribution to public understanding and, perhaps, a help to others.

2. BACKGROUND

Let me begin by briefly recalling the genesis of our work. At the beginning of this decade, the growth of plutonium stocks attracted renewed attention, not only because of the continued accumulation from civil operations but, still more, because of the sudden release of large quantities from weapons made surplus by disarmament treaties. Against this background, as you have heard, Dr. Blix, the Director General of the IAEA, convened in 1992 and 1993 informal discussions with representatives of a number of the States most directly concerned to review the situation and to consider the possibility of a role for the IAEA in the management of civil plutonium. These discussions did not produce clear-cut conclusions, but the participants decided it would be worthwhile to explore the subject further, outside the framework of the Agency but in informal contact with the Secretariat. After minor changes of membership, participants in these further informal discussions came from Belgium, China, France, Germany, Japan, the Russian Federation, Switzerland, the United Kingdom and the United States.

3. APPROACH

We quickly established the framework for our work. The basic elements were:

- First, commitment to the NPT, and to the safeguards and other non-proliferation commitments associated with it. No other basis was conceivable;

- Second, national responsibility for the management of nuclear materials and the nuclear fuel cycle;

- Third, upholding the existing international mechanisms for the regulation and control of plutonium and other nuclear materials. In particular, we were determined not to do anything which would undermine the Agency's safeguards system, nor did we wish to cut across the work on Programme 93+2;

- Fourth, we focused on civil material. We also decided against any attempt to anticipate negotiations on a possible Cut-Off Treaty.

We quickly concluded, however, that we needed to widen our approach in a number of ways:

- First, any scheme had to be able to accommodate plutonium from surplus warheads designated as no longer required for defence purposes. Once it is clear that such material is not needed for defence purposes, we believed that it should be assimilated to civil material so far as possible. We wanted to avoid the emergence of an ill-defined grey zone of material between civil and military, whose ambiguous nature could be exploited by would-be proliferators;

- Second, we came to the view that the factors which influence the size of, and changes in stocks of separated plutonium cannot be separated from those which influence other holdings of plutonium. A proper picture must give information on both in the context of a national strategy for the nuclear fuel cycle and all plutonium. What each country's strategy should be is of course, for it to decide in the light of its own position;

- Third, plutonium must be managed within the requirements not just of non-proliferation, but also of safety, physical security, good management, and the protection of workers, the public and the environment. These requirements and the commitments of Governments to meeting them needed to be an integral part of any scheme.

Within this framework, after considering the range of international controls, regulations and standards to which plutonium, like other nuclear materials, is subject, we came to the view that what was needed was not new controls, but measures to increase the public's understanding. We believe that greater openness - covering both increased transparency and the readiness to give reasonable explanations which must go with it - are the best way to win greater confidence from the public, nationally and internationally.

By contrast, we have not attempted to propose new institutional arrangements. We were naturally conscious of the extra effort which would be needed to negotiate anything of this kind and give it binding legal form. We also remembered that protracted efforts during the 1980s to negotiate such arrangements had run into the sand. More important, at a time when the future of nuclear power depends so much on public acceptance, it was our view that the creation of new inter-Governmental institutions did not deserve priority over an attempt to increase public understanding and public confidence.

4.   THE GUIDELINES

Let me now turn to describe the text which we have produced. It is a set of proposed Guidelines which we hope will be generally accepted as a framework for the responsible management of non-military plutonium in both NNWS and NWS. We envisage that, if they win acceptance, these Guidelines will be the object of a political commitment by Governments like those of the Guidelines of the Zangger Committee or those of the Nuclear Suppliers' Group.

The main features of this text are in summary:

- First, a codification of existing requirements and standards in the field of non-proliferation, safety, physical protection and national accounting for nuclear material to form a common baseline for all the countries who adopt the Guidelines;

- Second, a new commitment to the strategic management of each country's holdings of plutonium taking account of a number of specified factors. These are the need to avoid contributing to the risks of nuclear proliferation - especially during any extended period of storage, the need to protect the workers, the public and the environment, economic and financial factors and the importance of balancing supply of and demand for plutonium - including reasonable working stocks - as soon as practical;

- Third, a new commitment to transparency. Countries who adopt the Guidelines will undertake to publish occasional statements of their national strategies for nuclear power and the nuclear fuel cycle and, against that background, of their general plans for managing their holdings of plutonium.

- Fourth, to illustrate and confirm those plans, the Guidelines provide for the publication each year in an agreed format of the amounts of holdings of unirradiated plutonium and estimates of the amounts of plutonium contained in spent fuel in each country. (There is some hesitation about including the information on plutonium in spent fuel). The public will then be able to follow the implementation of national strategies and to put individual actions in context;

- Fifth, there are also detailed provisions on the control of international transfers and on the storage of separated plutonium. A system of end-use certificates is proposed to ensure that an export of plutonium does not proceed until the exporting and recipient Governments both understand, and are satisfied with the intended end-use, the amounts involved and the timetable. The storage of separated plutonium would also be controlled so as to avoid an undue increase in the number of sites where it is held.

The treatment of some points deserves to be explained in rather more detail.

- First, the Guidelines are designed to apply both to NNWS and NWS;

- Second, they apply to plutonium in all unirradiated forms;

- Third, they apply to plutonium in all peaceful nuclear uses;

- Fourth, plutonium designated as no longer required for defence purposes posed a delicate problem, especially since it was increasingly clear to us that the physical transfer from military to peaceful use cannot be instantaneous but may extend in different stages over a period of years;

After careful discussion, we agreed that the Guidelines should apply to such plutonium from the time that the Government concerned designates it to be no longer required for defence purposes;

- Fifth, as for safeguards, the basic principle embodied in the Guidelines is that each country should continue to be governed by its existing safeguards agreements;

- Sixth, in addition, in a supplementary provision, the NWS state their intention to bring under safeguards as soon as practicable plutonium which they have transferred to peaceful nuclear activities. This is in accordance with the Principles and Objectives for Nuclear Disarmament agreed at the NPT Conference in 1995;

  NWS are also considering whether to commit themselves to a similar intention in respect of other plutonium in peaceful nuclear use which has not been connected with their military programmes;

- Seventh, in order to avoid disclosing information which is commercially or economically sensitive or which needs to be protected for security reasons, the figures for holdings of plutonium will be published on a national basis only, and not broken down by ownership or location;

- Eighth, because Highly Enriched Uranium is also usable for weapons, the intention is to try to work out similar guidelines for its management;

5.   THE PROCESS OF DISCUSSION

I have already described our starting point and some of the main considerations which influenced our approach. It may also help to illuminate the process of discussions if I also tell you about those areas of our work which required the greatest effort:

- First, it will be no surprise that the treatment of surplus military plutonium and the extent of safeguards were the issues which bulked largest in our discussions;

- Second was the need to find ways to take account at different points of the differences between the nuclear industries in different countries - differences in size, in the number of undertakings, or types of commercial organisation or the degree of Government control or ownership;

- Third, great attention to detail was needed in working out standard formats for the information to be published; which we hope will give readers a clear overview, and whilst accommodating different arrangements and structures in different countries;

- Fourth, we had to allow at every stage for the different starting points in different countries, in terms of fuel cycles, plant, equipment and technical possibilities.

Although the preparation of the Guidelines has involved a great deal of work by participants with different initial points of view, it would be wrong to leave you with the impression of a divided and contentious group. The issues involved are real and important and I should like to record my sense of the constructive and friendly way in which participants in the discussions worked together to achieve a common goal. I should also like to thank Dr. Blix and the Agency's Secretariat for their tactful support throughout.

6. CONCLUSION

Faced with a scheme of this sort, it is reasonable to ask what practical difference it will make. Let me address that question by way of conclusion. It should be said at once that the adoption of these - or any other - Guidelines cannot transform the world. Stocks of plutonium and the physical possibilities for managing them and the problems which they cause will not change. The range of technical options will be the same so will be the problem of funding resources to implement any solutions which may be decided on.

What these Guidelines have the potential to do is to modify the way in which Governments approach plutonium-related decisions:

- The Guidelines would establish a basis for judging what approaches to plutonium-related problems are internationally acceptable;

- They would establish that surplus military plutonium should be treated in the same way as civil plutonium from the time that it is designated as no longer required for defence purposes and submitted to safeguards once it is transferred to peaceful nuclear activities;

- They would establish a new requirement for the active management of plutonium - other than that required for defence purposes - according to a strategy which takes into account a number of specified factors;

- New requirements on control of transfer and of storage should help to reduce proliferation risks.

These new elements are not a panacea and should not be oversold, but would be worthwhile improvements in the framework within which both nuclear operators and Governments address in future the management of plutonium.

Above all, the Guidelines embody a new commitment to transparency. If this is accepted, Governments will undertake a new commitment to publish, not only an explanation of their strategies for managing plutonium as part of the nuclear fuel cycle, but also information which sheds light on their progress. These changes would contribute to greater understanding of the framework of obligations and requirements within which nuclear operators and Governments manage plutonium, of what Governments and nuclear operators are trying to achieve and the ways in which they are trying to do it. The hope is that this increase of understanding will increase public confidence in this area of nuclear operations.

US-RUSSIA COOPERATION IN THE DISPOSITION OF WEAPONS GRADE FISSILE MATERIALS

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Abstract

In response to the changes in the international geopolitical scene, the United States and Russia have embarked in new directions regarding their nuclear weapons stockpiles. Both countries have entered a period in which significant numbers of nuclear weapons are being withdrawn from their stockpiles and dismantled. Large quantities of materials usable in weapons, including plutonium, are no longer required for defense purposes. On January 14, 1994, U.S. President Clinton and Russian President Yeltsin issued a statement on "Nonproliferation of Weapons of Mass Destruction and The Means of Their Delivery," in which the Presidents endorsed the goal of irreversibility of nuclear arms reductions and tasked their experts jointly to "study options for the long-term disposition of fissile materials, particularly of plutonium, taking into account the issues of nonproliferation, environmental protection, safety, and technical and economic factors." This paper traces the development of international technical cooperation on disposition of Russian weapons-grade plutonium, since disposition of Russian high enriched uranium is already being addressed by downblending into low enriched uranium for nuclear power reactor fuel. Development of options for disposition of plutonium has been addressed by diplomatic contacts between U.S. and Russia, followed by discussions and studies of disposition options by technical experts. This process has evolved into a recently-developed program of small-scale technology demonstrations that will support design of pilot facilities for disposition of plutonium. Experience gained in the operation of the pilot facilities will permit the design of full-scale plutonium disposition facilities to achieve irreversible disposition of plutonium as envisioned by the U.S. and Russian Presidents in their January 1994 statement. For this pressing problem, there remains technical work to be done, there remains political work to be done, and there remains financial work to be done.

1. BACKGROUND

In response to the changes in the international geopolitical scene, the United States and Russia have embarked in new directions regarding their nuclear weapons stockpiles. Both countries have entered a period in which significant numbers of nuclear weapons are being withdrawn from their stockpiles and dismantled. Large quantities of materials usable in weapons, including plutonium, are no longer required for defense purposes. On January 14, 1994, U.S. President Clinton and Russian President Yeltsin issued a statement on "Nonproliferation of Weapons of Mass Destruction and The Means of Their Delivery," in which the Presidents endorsed the goal of irreversibility of nuclear arms reductions and tasked their experts jointly to "study options for the long-term disposition of fissile materials, particularly of plutonium, taking into account the issues of nonproliferation, environmental protection, safety, and technical and economic factors." The April 1996 Summit on Nuclear Safety and Security of the leaders of the G-7 nations and Russia in Moscow focused additional attention on this pressing problem of international security. The assembled leaders agreed that these excess stockpiles should be reduced as soon as practicable, while ensuring effective nonproliferation controls, by means that would transform these materials "into spent fuel or other forms equally unusable for nuclear weapons." Disposition of U.S. weapons grade plutonium and high enriched uranium are discussed at this Symposium in the paper on "The U.S. Program for Disposition of Excess Weapons Plutonium" by M. Bunn (see page 79 of this publication).

This paper traces the development of bilateral U.S./Russian technical cooperation on disposition of Russian weapons-grade plutonium. Disposition of Russian highly enriched uranium is already being addressed by downblending into low enriched uranium for nuclear power reactor fuel. Other countries besides the U.S. have expressed interest in assisting the Russians or are working with Russia on preparation for disposal of these excess weapons plutonium. For example, as an outgrowth of its AIDA-MOX program, France, in cooperation with Germany, has proposed a "DEMOX" pilot facility in Russia to produce mixed oxide (MOX) fuel for plutonium disposition in Russian power reactors.

Development of options for disposition of plutonium has been addressed by diplomatic contacts between the USA and Russia, followed by discussions and studies of disposition options by technical experts. This process has evolved into a recently-developed program of small-scale technology demonstrations that will support design of pilot facilities for disposition of plutonium. Experience gained in the operation of the pilot facilities will permit the design of full-scale plutonium disposition facilities to achieve irreversible disposition of plutonium as envisioned by the U.S. and Russian Presidents in their January 1994 statement.

2.   EARLY HISTORY OF U.S./RUSSIAN COOPERATION

A U.S./Russian meeting on the Disposition of Plutonium, in accordance with the January 14, 1994 statement by the Presidents, was convened in January 1995. The purpose of that meeting was to initiate study of alternatives for the long term disposition of plutonium resulting from the dismantlement of nuclear armaments, taking into consideration nuclear nonproliferation, safety, environmental protection, and technical and economic factors. After reviewing technical presentations on research related to plutonium disposition alternatives, the U.S. and Russian sides agreed to conduct joint work to develop consistent comparisons of the agreed-upon plutonium disposition alternatives. The anticipated result of this work was to be a report for presentation to appropriate governmental organizations of both sides. This report would address nuclear nonproliferation, safety, environmental protection, and technical and economic factors.

3.   JOINT UNITED STATES/RUSSIAN STEERING COMMITTEE

A U.S./Russian Joint Steering Committee on Plutonium Disposition, which coordinates and approves joint technical work on plutonium disposition, was formed in late September, 1995. The Joint Steering Committee meets alternately in the U.S. and Russia to review results of technical research, and to review and approve proposals for additional research, testing, and small-scale demonstration experiments performed primarily in Russia. The Joint Steering Committee directs the work of Technical Working Groups established as required for each technical area (Water Reactors, Fast Reactors, Immobilization, and Pit Disassembly and Conversion). Each Technical Working Group has U.S. and Russian co-chairs, and adds U.S. and Russian technical specialists as required to perform its work. The Joint Steering Committee has been performing its work under the authority of the January 14, 1994 statement of Presidents Yeltsin and Clinton, and under a subsequent agreement between Secretary of Energy O'Leary and Minister of Atomic Energy Mikhailov signed on August 20, 1996.

4.   DEFINITION OF JOINT UNITED STATES/RUSSIAN PLUTONIUM DISPOSITION STUDY

In October, 1995 the technical working groups under the guidance of the Joint Steering Committee initiated a study of the identified plutonium disposition options. The goal of the study was to provide decision makers with a set of consistently evaluated plutonium disposition options.

This goal was to be reached by a two component process: establishing a commonly agreed upon set of technical facts relating to plutonium disposition technology, and establishing a basis for economic evaluation of the disposition options. The deliverable was a report providing a consistent comparison of a range of options for plutonium disposition, using the criteria specified by the two Presidents, for presentation to appropriate governmental organizations of both nations.

Each option was evaluated against the criteria specified by the presidents:

- Nonproliferation: Provide resistance to theft or diversion, resistance to retrieval, extraction or reuse, and timeliness in beginning and completing disposition.

- Environmental Protection and Safety: Meet established standards of environmental protection and public and worker health and safety.

- Technical Factors: Assess technical viability and technical readiness of each step in the disposition process.

- Economic Factors: Implement the disposition options in a cost-effective manner.

- Public and Institutional Acceptance: Evaluate the prospect for achieving public and institutional approval, steps in the process for which it may be particularly difficult to gain approval, and actions that could be taken to increase the chances of success.

Joint Working Groups were established for analysis of each alternative for plutonium management. Two cross-cutting working groups, economics and nonproliferation, were established to ensure consistent comparisons of all the options in those areas. The technical working groups were based on the following relatively mature plutonium disposition options:

WATER REACTORS: Water reactors belong to the most common types of reactors used both in Russia and the U.S. In Western Europe, there is considerable experience in use of plutonium as a component of mixed oxide as fuel for such reactors. Neither Russia nor the U.S. has large scale experience with water reactor mixed oxide fuel or large scale facilities for producing mixed oxide fuel.

FAST REACTORS: Russia has one fast reactor, the BN-600 at Beloyarsk, and has experience in the utilization of plutonium, including weapons grade plutonium, in fast neutron reactors. U.S. experience is more limited; the U.S. has recently terminated its fast reactor program.

LONG-TERM STORAGE: The plutonium being removed from dismantled nuclear weapons, as well as that from separated spent nuclear fuel, requires safe and secure long term storage. Such storage is essential for all options.

BURIAL IN GEOLOGICAL FORMATIONS: Both the U.S. and Russia have developed technologies for geologic repositories and deep boreholes, but neither country has experience in geologic disposal of plutonium. The U.S. was studying such disposal.

IMMOBILIZATION: Both the U.S. and Russia have some experience in immobilizing high level radioactive waste in borosilicate glasses and other materials. However, neither country has experience in large scale immobilization of plutonium. The U.S. was studying options for large scale immobilization of plutonium, and both countries are interested in the possibility for immobilization of scrap and residues.

STABILIZATION OF SOLUTIONS AND OTHER FORMS: Both the U.S. and Russia have some plutonium in unstable forms that are not suitable for extended storage. Both countries have an

interest in examining options for stabilizing these materials in preparation for long term storage and disposition. The task of this group was to consider stabilization measures for this limited quantity of plutonium, not to consider an option for disposition of the larger total quantity of excess plutonium.

5. REPORT OF JOINT UNITED STATES/RUSSIAN PLUTONIUM DISPOSITION STUDY

As a baseline for the study, disposition of 50 tonnes of excess plutonium in each country was assumed, with illustrative estimates for disposition of 75 and 100 tonnes to clarify economic impacts of increased disposition amounts. The report consists of a very short Executive Summary; a longer Summary Report on all aspects of the study; and a series of final technical reports on technically-mature disposal options: Water Reactors, Fast Reactors, Storage, Geologic Disposal, Immobilization, Conversion and Stabilization, and Nonproliferation. Technical reports on the technically less mature disposition options (High-Temperature Gas-Cooled Reactors and Accelerator-Based Conversion) were prepared by the Russian Federation and were also included. English and Russian versions of the report text were approved in August, 1996. The English-language version of the full report was published in September, 1996 [1] and the Russian-language version was received in March 1997. A combined English/Russian version of only the Executive Summary and Summary Reports has also been prepared.

The Joint U.S./Russian Plutonium Disposition Study considered both first steps in managing excess plutonium - including secure storage, conversion of plutonium weapons components to other forms, and stabilization of unstable forms of plutonium - and options for disposition of excess plutonium. These options include use as fuel in water reactors and fast reactors (Russia only), and immobilization in glass or ceramics. Ensuring effective nonproliferation control was to be achieved by meeting the "spent fuel standard" [2], according to which the plutonium would be transformed "into spent fuel or other forms equally unusable for nuclear weapons." It concluded that each of these options could accomplish the mission of disposition of the 50 tonnes of excess weapons plutonium assumed for analysis over the next two to four decades, while meeting the criteria of nonproliferation, safety, and protection of health and the environment. Each of the options was judged to be technically feasible, though they are not equally technically mature. For both the United States and Russia, reactor options involving known and demonstrated reactors and MOX fabrication technologies were judged to have the highest level of technical maturity, followed by immobilization technologies that have been demonstrated with high-level wastes containing trace quantities of plutonium.

Stringent standards of physical protection, control, and accounting should be maintained throughout the process of disposition, regardless of the option chosen. The process of converting plutonium weapons components to other forms, when the material is still in an extremely attractive form for weapons use, requires particular attention to security and accounting, but is common to all the options. Bilateral monitoring can be a useful initial step, and might be possible to apply earlier in the process than IAEA safeguards. International safeguards could be applied to the plutonium as soon as it is converted from weapon component form (also referred to as a "pit" in the U.S.) to a metallic ingot or oxide powder which does not reveal sensitive weapon design information.

The most timely disposition options were judged to be the immobilization and reactor options, both of which are capable of accomplishing disposition of 50 tonnes of plutonium within 20 - 40 years from when the program begins. While geologic disposal of immobilized plutonium in deep boreholes technically could be the quickest option to implement, the period required to immobilize plutonium, to select an appropriate site, to substantiate the environmental safety of this site, and to acquire the needed licenses and political approvals could be quite long. In addition, MINATOM believes that in Russia, where the official policy is to separate plutonium from spent fuel for civilian use, plutonium immobilization approaches would require gaining new licenses and

political approvals for geologic emplacement of plutonium-bearing materials; such approvals could be difficult to obtain.

To accomplish plutonium disposition more quickly, Russia is considering the use of both fast-neutron and thermal-neutron reactors, including future reactors as they become available. There are eleven operating VVER-1000 reactors in the Ukraine that might be used along with Russia's seven operating VVER-1000 reactors for disposition of some of Russia's excess plutonium. Canada has suggested that both U.S. and Russian excess weapons plutonium might be burned as fuel in Canadian reactors, with the MOX fuel fabricated in the U.S. and Russia.

The report concludes that the primary obstacles to accomplishing plutonium disposition are not technical but financial and political: the need to finance the large initial capital investments required for all options, and the need to gain necessary licensing and political approvals. All of the options considered would require initial capital investments of hundreds of millions, or billions, of dollars. Options involving maximum use of existing facilities generally would be less costly than options requiring major new construction. All of the options considered are capable of meeting high standards of protection for environment, safety, and public health, if sufficient resources are applied. The United States and Russia need not use the same plutonium disposition technology. Indeed, given the very different economic circumstances, nuclear infrastructures, and fuel cycle policies in the two countries, it is possible that the best approaches will be somewhat different in the two countries.

In both countries, secure interim storage is an essential first step for all options; processing plutonium from weapons components or other forms is also an essential step for both countries, and will involve substantial effort. In addition, disposition of U.S. and Russian excess weapons plutonium should proceed in parallel, with the goal of reductions to equal levels of military plutonium stockpiles. To facilitate the objective of disposition as rapidly as practical, if the reactor option is pursued, the resulting material should not be reprocessed and recycled at least until current excess stockpiles of separated plutonium are eliminated.

6.   JOINT UNITED STATES/RUSSIAN TECHNICAL PROJECTS ON PLUTONIUM DISPOSITION

As the results of the Joint U.S./Russian Plutonium Disposition Study began to emerge, the focus of the U.S./Russian cooperation began to shift from conceptual studies to laboratory scale experiments (i.e., small scale demonstration experiments using plutonium from dismantled weapons), and initial work supporting safety analyses and approvals which would be required for Russian implementation of disposition options.

In May 1996 the Joint Steering Committee approved the following projects:

• Validation of computer codes for modeling safety of weapon-grade MOX use in VVER-1000 reactors;

• Fabrication of VVER-1000 MOX with plutonium from dismantled nuclear weapons;

• Fabrication of CANDU MOX pellets with plutonium from dismantled nuclear weapons, for shipment to Canada for irradiation in the Chalk River test reactor (in support of the PARALLEX project);

• Tests and demonstrations of immobilization of plutonium in glass;

• Evaluation of the Russian cold wall crucible for immobilization on plutonium;

- Tests and analysis of plutonium sorption in rock, modeling its behavior in geologic repositories;

- Use of U.S. safety codes to analyze conversion of the existing BN-600 reactor to a plutonium "burner."

One demonstration project involves trilateral international cooperation. Canada has suggested that both U.S. and Russian excess weapons plutonium might be burned as MOX fuel in Canadian heavy water CANDU reactors. In this option, MOX fuel containing excess weapons plutonium would be manufactured in both the United States and Russia, shipped to Canada, burned in Canadian CANDU reactors, and the spent fuel would be retained for disposal by Canada. To demonstrate the necessary technology and exercise the required governmental approvals, a parallel experiment ("PARALLEX") was proposed: a small amount of MOX fuel containing U.S. excess weapons plutonium would be fabricated and shipped to Canada, and a similar amount of MOX fuel containing Russian excess weapons plutonium would also be fabricated in Russia and shipped to Canada. The U.S. and Russian fuel would be irradiated in a Canadian test reactor at Chalk River, thus demonstrating plutonium disposition in a third country on an early time scale.

Contracts for most of the preceding projects have now been negotiated with participating Russian institutes, with specific milestones, deliverables, and payments. The technical work performed in Russia under each contract is done in cooperation with an appropriate U.S. National Laboratory. Contract deliverables in the form of reports, technical information exchanges, and laboratory research results now are being received under these contracts.

Pit disassembly and subsequent conversion to plutonium oxide powder form is a requirement for all disposition options. As powder, the plutonium can be subjected to international verification without compromising sensitive weapon information. This would represent a very significant step forward toward nonproliferation goals. Therefore a recent focus of U.S./Russian cooperative effort has been initiating the development of a Pit Disassembly and Conversion/Non Destructive Assay Pilot Facility. The pit disassembly and conversion process could be based on one of several technologies under development in the U.S. and Russia. Since the preferred disposition option in Russia is to burn the excess plutonium as MOX fuel in Russian reactors, the choice of a pit conversion process will be determined by such factors as environmental impact, importance of impurities to MOX fuel performance, and the characteristics of the plutonium oxide powder which permit manufacturing of MOX fuel to accepted specifications. At the most recent Joint Steering Committee meeting in Los Alamos, New Mexico, U.S., the Committee therefore approved proceeding with a feasibility study of an Integrated Pit Disassembly and Conversion Pilot Line, and an Integrated Non-Destructive Assay System. A portion of the funding will be used in Russia to compare several candidate chemical processes for conversion of plutonium from metal to oxide. In particular, the oxide powder produced by each candidate conversion process will be evaluated with regard to the quality of the MOX fuel pellets which can be produced from it. A fuel specification which is compatible with Russian reactor standards and the requirements of the MOX fuel fabrication process (e.g. the French/German DEMOX plant requirements or accepted European MOX fuel standards) is expected to result from this work.

7. U.S. RECORD OF DECISION ON PLUTONIUM DISPOSITION OPTIONS

On January 14, 1997, the United States Department of Energy (USDOE) issued a "Record of Decision for the Storage and Disposition of Weapons-Usable Fissile Materials Final Programmatic Environmental Impact Statement." The DOE announced its decision to pursue a dual path for plutonium disposition: "DOE's strategy for disposition of surplus plutonium is to pursue an approach that allows immobilization of surplus plutonium in glass or ceramic material for disposal in a geologic repository pursuant to the Nuclear Waste Policy Act, and burning of some of the surplus

plutonium as mixed oxide (MOX) fuel in existing, domestic, commercial reactors, with subsequent disposal of the spent fuel in a geologic repository pursuant to the Nuclear Waste Policy Act."

8.   CONCLUSIONS

The problem of disposition of excess weapons plutonium is a substantial and difficult one. Early agreement at the highest political level by the U.S. and Russia allowed a substantial technical study to be done on a mutual, bilateral basis. The U.S. and Russia have taken significant initial steps in designating national leaders for this effort, in identifying appropriate experts, in identifying and agreeing on options, and in beginning some initial small-scale demonstrations. Still, much remains to be done, and the effort required clearly is too large for just the U.S. and Russia. Also it is clear that no single government can finance the effort needed.

For this pressing problem, there remains technical work to be done, there remains political work to be done, and there remains financial work to be done. The world community must be prepared to contribute to all of these.

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NUCLEAR ENERGY IN ASIA AND REGIONAL CO-OPERATION

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Abstract

There is increasing concern in East Asia about regional cooperation in the field of nuclear power. At the APEC conference in Osaka in 1995, APEC (Asia Pacific Economic Cooperation) established an Energy Research Center. The center has started to perform joint research forecasts on energy supply and demand for the region. Japan proposed the inauguration of a Conference on Nuclear Safety in Asia at the Moscow Nuclear Energy Summit in 1996. The first conference was held in Tokyo that year. This year, the conference will be held in Seoul. Japan's Atomic Energy Commission sponsors the International Conference for Nuclear Cooperation in Asia every year. This year marks the eighth conference. The outstanding feature of this year's conference was that so many countries stressed regional cooperation. South Korea proposed the installation of a regional online radiation monitoring system. The Philippines asserted the need for a cooperative mechanism on the lines of ASIATOM. Why is so much concern now being focused on nuclear power cooperation in East Asia? What kind of regional cooperation is necessary, and what kind is possible? What are the unique features of nuclear power cooperation in East Asia? These are the points addressed in this paper.

1. THE NEED FOR REGIONAL COOPERATION

Use of nuclear power is expanding in East Asia. Japan has 51 nuclear power generating stations, South Korea 11, and Chinese Taipei 6. These supply 30 or even 40 percent of electrical power, and expansion of facilities is continuing. Three stations are in operation in China, but rapid expansion of nuclear power generation is being promoted. The plan is to reach power generation on the scale of 40 million or even 60 million kilowatts by 2020. Nuclear power generation plans are being finalized in Indonesia and North Korea, and introduction of nuclear power is being studied in Thailand and Vietnam. At present there are 70 nuclear power generating stations in East Asia, but if those under construction and those in planning are included, the total approaches 100 stations, a level comparable with the 109 stations in the U.S.

The World Bank has issued a report entitled "The East Asian Miracle." As this title indicates, economic growth in East Asia is extremely rapid and this growth is forecasted to continue in the future. Energy demand is also expanding rapidly. On the other hand, Japan, South Korea and Chinese Taipei have few energy resources. The ASEAN region is also expected to become an oil-importing region in the 21st century. Dependence on external sources of oil in East Asia was 50% in 1980, but is expected to reach 70% in 2010. East Asia is threatened by a grave energy crisis. Not only that, there is an increasing need to suppress the use of fossil fuels in order to prevent global warming.

Nuclear energy does not require large-scale imports, and is low in cost. Therefore, it is an attractive option for East Asia. East Asia also has few uranium deposits. Japan and China are planning to utilize plutonium, but most countries are promoting the use of plutonium in the future. Some predict that "The West will decline along with fossil fuels in the 21st century, while the East will prosper owing to nuclear energy." East Asia is sure to become a huge nuclear power market. France, Canada, and Russia are already competing to market nuclear power generation in East Asia, but South Korea and China are also planning to export nuclear power. The U.S. and Japan are lagging behind in this area, but are striving to make a comeback.

East Asian countries are concluding bilateral nuclear power cooperation agreements with each other or with countries in Europe and North America. But if nuclear power usage expands within the region, multilateral cooperation will be vital in order to ensure safety, to promote the nuclear fuel cycle, and to prevent nuclear weapons proliferation.

2.   FEATURES OF INTERNATIONAL RELATIONS IN EAST ASIA

The goals and forms of regional cooperation in nuclear power are stipulated by the political, social and cultural conditions of the region. The primary feature of the East Asian region is that no international framework on a multilateral basis has yet been developed in terms of politics, economics or security. The foundations for regional cooperation in nuclear power are therefore weak.

With the end of the cold war, in Europe, Germany has reunited, the machinery of the Warsaw Pact has been dismantled, and international unification is progressing in the EU. An international framework for multilateral interdependence is already beginning to take a firm hold.

In East Asia, on the other hand, bilateral military alliance systems are continuing since the end of the cold war, even without an already-existing framework for multilateral security. Major military forces exist within the region and the partitioning of the Korean peninsula is a continuing problem. Chinese Taipei possesses many nuclear generating plants, but does not participate in either the IAEA or the NPT.

East Asia has achieved success in economic development and signs of economic interdependence may be seen in many areas. However, the security system is still immature. The power politics of the cold war still hold sway in East Asia. The APEC organization spans the entire Asia-Pacific region, and has formulated policies with mutual targets of liberalization, with the goal of freedom of trade and investment. However, discussion of security issues has made little headway. Multilateral interdependence may be termed the basis for the international order in the post cold war era. Movements in that direction may also be seen in East Asia.

Cooperation between the ASEAN nations is expanding and deepening, and ASEAN is going to attain a 10-nation system. The Asean Regional Forum (ARF) has been established for discussion of security issues, and an anti-nuclear weapons convention has already been concluded.

There is currently no movement in Northeast Asia to form a mechanism for a regional security organization. However, the need for such a forum in Northeast Asia is receiving wider recognition.

Most developing countries in East Asia adopt non-democratic authoritarian political systems in order to achieve more rapid economic development. In not a few cases, these regimes form ties with economic conglomerates to form privileged classes. However, the progress of economic cooperation and the flow of information due to the development of information technology are encouraging democratization in many countries and are also furthering multilateral international cooperation.

Development of nuclear power is directly linked to the energy issues faced by each country. Its development will take a long time. Substantial international cooperation and interdependence cannot be successfully achieved without sturdy bonds of international trust. Nuclear energy cooperation in East Asia will be maintained to nurture relations of international trust in the region and thereby further develop cooperation in the field of
nuclear power.

China, with its rapid economic development, is a major concern for the countries of East Asia from the standpoints of politics, economics, and security. Some view most problems in East Asia as a "China problem." Participation by China is essential in any international framework for East Asia.

The second feature of East Asia is the way that cooperation is promoted. As can be seen in the deliberations of ASEAN and APEC, international relations in East Asia follow a pattern in which actual results are accumulated through a time-consuming process in which compromises are worked out through repeated discussion. Because most countries in the region are in the process of unifying their peoples, and they have a diversity of political systems, religions, cultures, and stages of economic development.

Furthermore, in East Asia the cooperative entity is viewed as more important than the individual. Consensus and harmony are deemed most important. In one opinion survey, 82% of Americans viewed "individual freedom" as an important value, while only 32% did in East Asia. Conversely, 71% of East Asians valued an "orderly society," while the corresponding figure in America was 11%.

Almost all of the world's nuclear power today is being generated in developed countries. The central target of IAEA activities has been the developed countries. These are societies that have accepted rationalism based on the philosophical foundation of Western European society. But East Asia is different.

Human rights foreign policies push the values of Western Europe. But this causes friction in the Asian region. The same holds true in foreign relations related to nuclear power. In Asia, the security measures of the IAEA are criticized as too intrusive and too costly. When it comes to nuclear materials control, instead of excessively strict quantitative standards based on a logical basis, in East Asia relations based on trust may well be a more appropriate means to prevent nuclear weapons proliferation.

The keynote of international cooperation in East Asia is gradualism and practicality.

3.   NUCLEAR POWER COOPERATION ISSUES

Well then, what kind of nuclear power cooperation is needed in East Asia, and what kind is possible? The most urgent issues are ensuring safety, attaining public acceptance, intermediate storage of spent fuel, and disposal of radioactive waste. From the long-term perspective, the issues that need to be addressed are formation of a regional safeguards system and research and development.

3.1. Ensuring safety

The first issue is the need to ensure safety. If a nuclear power plant accident occurs, its effects will spread to neighboring countries. Nuclear power generation is expanding at a rapid pace in the Asian region, and more and more countries are introducing it. Ensuring safety is an urgent issue for all, and international cooperation is vital.

In Japan, efforts to train nuclear power plant operators and dispatch technical experts are being furthered on a bilateral basis, based on cooperation between government and private industry. However, the following issues must be addressed for cooperation to take place on a regional basis.

*   Raising awareness of the need for ensuring safety in each country;

*   Promoting the acceptance of international decisions related to nuclear power safety by each country;

*   Building systems for emergency notification and mutual support in the event of accidents;

*   Adjustment of indemnification systems for damages to third-party countries within the region;

*   Ensuring the safety of materials and equipment supplied by countries that supply them.

Another issue that needs future study is the standardization of safety criteria and safety regulation methods.

3.2. Public acceptance

Second, public acceptance is increasingly vital for international cooperation.

In recent years, anti-nuclear movements in East Asia have been forming ties on an international basis. One recent trend is for demonstrators from neighboring countries to gather at demonstrations at nuclear power sites. "No Nukes Asia" forums have been held in various regions. Television is spreading in Asia, and many television stations that broadcast across borders are being established. There is an increasing danger that information about nuclear power may spread on a wide area basis in a sensational manner.

Public acceptance (PA) information has been exchanged at Asia Regional Nuclear Power Conferences until now. In 1992, an Asia network was set up between participating countries. However, a more organized response is needed.

3.3. Intermediate storage of spent fuel

Control of spent fuel is an issue that all countries face in common. There is a need to rapidly investigate the setting up of a framework for international cooperation in this area. South Korea and Chinese Taipei have adopted guidelines of not reprocessing fuel, due to the strong urging of the United States. Control of spent fuel has become a serious problem. Japan and China have adopted policies of reprocessing fuel and utilizing plutonium. However, even in Japan, the spent fuel that exceeds the amount to be reprocessed must be stored. And in China, it will be a long time before commercial reprocessing gets on line.

From the standpoint of preventing nuclear weapons proliferation, centralized control is the best method for storage of spent fuel. This issue must be tackled internationally in order to obtain agreement in society as well.

Utilization of plutonium may well become necessary in the future in East Asia, depending on the energy situation. To prepare for this eventuality, initiating a study to formulate a regional reprocessing plan would be of great significance.

3.4. Cooperation in waste materials policies

Each country is fundamentally responsible for the disposal of radioactive waste. Chinese Taipei has entrusted North Korea with control of its low-level radioactive wastes, bringing about a strong negative reaction from China and South Korea. Disposal of low-level radioactive wastes is more of a social problem than an technological one. An international response to this issue by the East Asian region as a whole would be of great advantage in forming internal agreement within the respective countries.

Of course, disposal of highly radioactive wastes is also a problem we all must face in common. Joint research in this area would be highly significant, both from the standpoint of cost and from the standpoint of PA.

3.5. A regional safeguards system

The fifth issue is the construction of a regional safeguards system with the significant goal of regional cooperation in the nuclear power field.

East Asia has achieved economic success, but is still immature in the area of security. Some say that, "Although no Japanese people think that Japan will arm itself with nuclear weapons, no one in neighboring countries believes that Japan will not arm itself with nuclear weapons." Deep-rooted concerns remain about the development of nuclear weapons on the Korean peninsula. The essential condition for nuclear power to develop smoothly in the East Asian region is for these concerns to be completely cleared up.

Furthermore, the best method for resolving fears about nuclear arms is for countries to be able to grasp actual conditions in neighboring countries through inspection of nuclear facilities in those countries under a system of regional safeguards.

In Southeast Asia, there is a ASEAN regional forum for discussion of regional security. A non-nuclear zone has also been established there. There are proposals for the establishment of a non-nuclear zone in Northeast Asia as well. A declaration against nuclearization of the Korean Peninsula for South Korea and North Korea was developed in 1992. There are proposals for Japan to participate in this, and for the participation of Chinese Taipei and Mongolia. Proposals have also been made seeking the participation of the U.S., Russia and China. Whatever the proposal, a regional safeguards system would take on great significance as a means of backing it up.

The necessary steps for establishing a regional safeguards system would be as follows. In its first stage, it would provide an improved and standardized system for quantitative control of nuclear materials in each participating country. In the second stage, data would be exchanged and mutual inspections performed between the measurement and control systems in the participating countries. In the third stage, the internal systems would be unified into a structure like that of Euratom.

I think that KEDO should serve as an important cornerstone for the development of such mechanisms. I also believe it is necessary to study effective systems for combining the regional safeguards with those of the IAEA.

3.6. Research and development

Cooperation in nuclear power research and development would raise the level of research and development within the region. At the same time, it would promote the development of interdependent relations. In order to research the issues of common concern throughout the region, the idea of establishing a joint East Asian Nuclear Power Research Institute may be attractive. Centralized research would be especially advantageous for future utilization of plutonium, since it would raise the level of transparency.

Proposals have been made for an ASIATOM or PACIATOM mechanism for East Asian nuclear power regional cooperation. The definitions of what these would entail are not entirely worked out, but the general idea is that ASIATOM would be a mechanism for countries in Asia and that PACIATOM would also include the U.S. and Canada, etc.

For regional cooperation in East Asia, it will not be appropriate to construct all-embracing mechanisms from the very start. It will be more practical for cooperation on necessary issues to proceed between the necessary countries.

We should utilize the already-existing organizations, such as APEC and WANO to further international cooperation on nuclear power in East Asia.

As various forms of cooperation progress, these will at last unite into an overall mechanism for the East Asian region. It will have functions similar to those of Euratom, and will perhaps become a reality around the year 2020.

INTERNATIONAL CO-OPERATION WITH REGARD TO REGIONAL REPOSITORIES FOR RADIOACTIVE WASTE DISPOSAL

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Abstract

The feasibility of an international waste management system for high level radioactive waste (HLW) and spent nuclear fuel (SNF), based on common interim storage, conditioning and final disposal facilities has been investigated. The approach adopted in this investigation was first, to establish the need for an international waste management facility of this kind; second, to define the system concept; third, to evaluate the concept in terms of its technical, economic, financial, institutional and ethical aspects; fourth, to examine the potential benefits of the system; and finally, to propose typical stakeholder profiles for participants in the system. The system concept appears to be entirely feasible from the point of view of a group of countries, each of which is generating HLW and SNF in such quantities as to render individual domestic final disposal facilities unrealistic, wishing to dispose of this material in a common safe and viable disposal facility provided by one of the participating countries.

1. THE INTERNATIONAL WORKING GROUP

The International Working Group (IWG) was formed in September 1994 to investigate, on an informal basis, the feasibility of an international high level waste and spent nuclear fuel management system, centred around the concept of a common final repository facility.

The members of the group were: Mr P J Bredell, Atomic Energy Corporation of South Africa Ltd (South Africa); Mr W Davis, Energy Resources of Australia Ltd (Australia); Dr H D Fuchs, Gesellschaft für Nuklear Service mah (Germany); Mr Y Hao, China Nuclear Energy Industry Corporation (PRC); Mr W Heni, Gemeinschaftskernkraftwerk Neckar GmbH (Germany); Dr F J Hoop, Elektrizitätsgesellschaft Laufenburg AG (Switzerland); Dr J P Lempert, Deutsche Gesellschaft zum Bau und Betrieb von Endlagern für Abfallstoffe mbH (Germany).

This paper is based on a report [1] produced by the IWG upon conclusion of its deliberations in September 1996.

2. PURPOSE AND METHODOLOGY OF THE INTERNATIONAL WORKING GROUP

The IWG endeavoured, first of all, to determine the need for an international high level waste (HLW) and spent nuclear fuel (SNF) management system, centred around the concept of a regional repository.

The IWG then defined a general concept for international HLW and SNF management in accordance with the principles and standards of radioactive waste management as recommended in the IAEA's safety documentation [2].

This concept was evaluated in terms of its technical, economic, financial, institutional and ethical aspects in order to determine the implications likely to be encountered at the level of concept implementation.

The potential benefits (and drawback's) to countries willing to participate in a venture based on this concept are assessed in general terms.

Finally, the IWG aimed to define as generally as possible, the expected stakeholder profiles of both offering as well as receiving countries wishing to participate in the HLW and/or SNF management system.

The methodology outlined above is schematically shown in Fig. 1.

3.   THE NEED FOR AN INTERNATIONAL HLW/SNF MANAGEMENT SYSTEM

There are basically two approaches to spent fuel management, the one is to reprocess the spent fuel by extracting the remaining uranium and plutonium from the spent fuel, thus leaving high level radioactive waste behind; the other is to keep the spent fuel intact. In both cases there is a final disposal challenge; either the high level radioactive waste is disposed of after reprocessing, or the spent fuel as such is disposed of directly. The choice of approach depends not only on the economics of the process, but also on various other considerations such as the goals of national nuclear power programmes for instance.
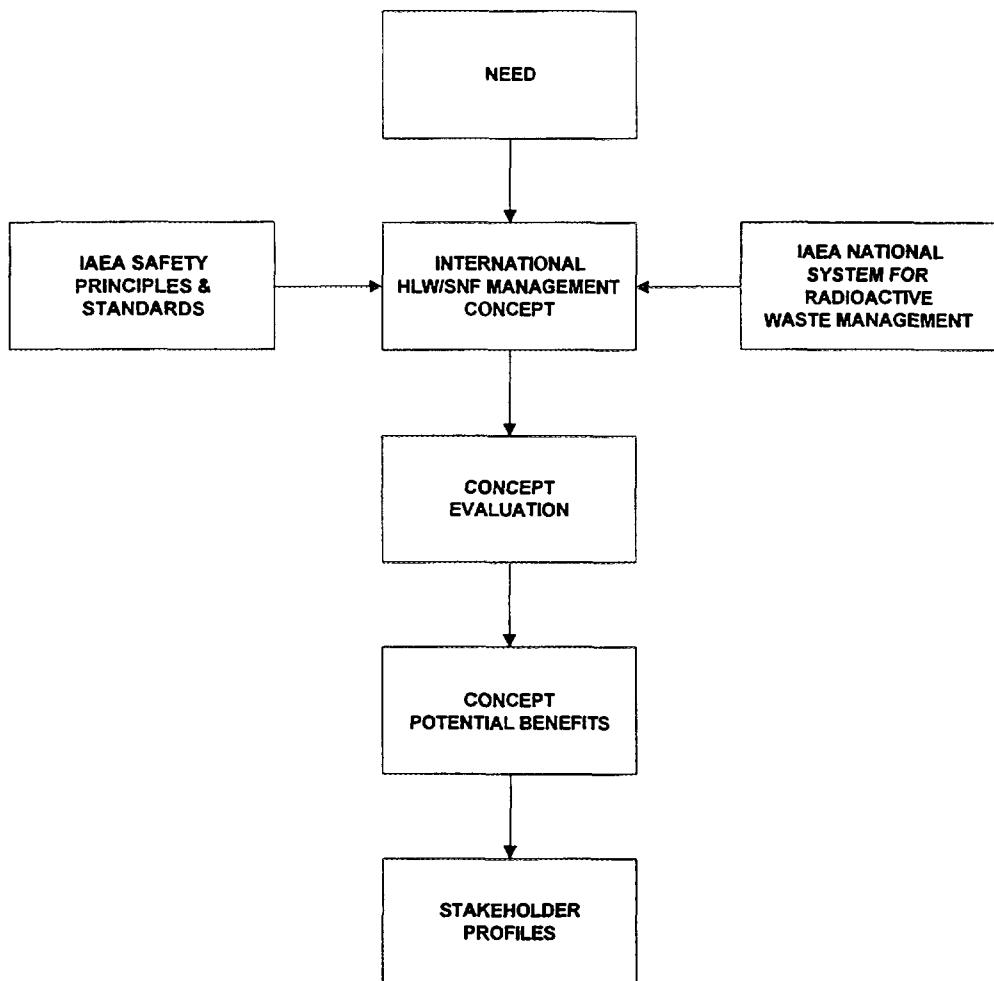

FIG. 1. Overall scheme for investigating the international HLW/SNF management system.

A categorisation of countries in terms of their expected spent fuel inventories by the year 2010 is given in Table I. Although the basis of the above categorisation is relatively arbitrary it serves the purpose of separating the small players (Category A) from the medium (Category B) and the large (Category C) players in spent fuel management. Similar figures are not available for HLW.

The development of a waste management system that satisfies appropriate safety criteria, requires the availability of extensive technical and economic resources. Some of the countries generating HLW/SNF have limited potential to mobilise sufficient resources to develop such a system. Others have the potential to develop such a system, including a geological repository, but the limited size of their nuclear power programmes does not justify the undertaking on economic grounds.

It is therefore not surprising that the need has been expressed for international cooperation in managing the high level radioactive waste (HLW) and spent nuclear fuel (SNF) produced in countries which cannot finally dispose of these wastes in a feasible manner within their own national borders.

The establishment of international repositories has been suggested in the past, and a number of studies has been undertaken [3, 4, 6] to address the inherent difficulties associated with the disposal of limited amounts of HLW/SNF exclusively within national borders. In this study, an approach towards the establishment of an international HLW/SNF management system is proposed, with the emphasis on the interactive process taking place between the countries participating in such a system.

All countries listed in Table I, with the exception of some central European countries which were closely associated with the former Soviet Union, are presently engaged in exclusive national spent fuel (or reprocessing) management programmes. Such central European countries had, and in some cases still have agreements with the Russian Federation to take back the spent fuel originally supplied to them by the Russian Federation or the former Soviet Union.

In summary therefore, the need for an international HLW/SNF management system could be defined as cooperation among countries

- to meet internationally recognised safety standards
- to develop and transfer relevant waste management technology
- to reduce the cost of establishing the required facilities
- to mobilise requisite resources, and
- to seek a permanent solution for the disposal of HLW/SNF.

4.   THE DEFINITION OF AN INTERNATIONAL HLW/SNF MANAGEMENT CONCEPT

The concept for international HLW/SNF management defined in this study is based on the IAEA documents, entitled *Principles of Radioactive Waste Management* [2] and *National System for Radioactive Waste Management* [5]. The National System for Radioactive Waste Management is the IAEA's contribution towards establishing and promoting, in a coherent and comprehensive manner, the basic safety philosophy for radioactive waste management and the steps necessary to ensure its implementation.   The above documents form part of the *Radioactive Waste Safety Standards* (RADWASS) Programme of the IAEA, and reflect the existing international consensus in the approaches and methodologies for safe radioactive waste management.

The concept for HLW/SNF management, proposed in this report, is based on the assumption that repositories, regardless whether they operate at national or international level, have to be treated in a similar fashion as far as the application of safety principles and standards are concerned; that is, similar criteria, evaluations and procedures apply at both the national and international level.

TABLE I. CLASSIFICATION OF COUNTRIES ACCORDING
TO SPENT FUEL INVENTORIES EXPECTED BY 2010

CATEGORY	COUNTRY	SPENT FUEL INVENTORY (tHM)
A (Less than 1000 tHM)	Pakistan	302
	Armenia	354
	Slovenia	382
	Netherlands	468
	Brazil	553
	Mexico	607
	South Africa	830
	Czech Republic	978
B (Greater than 1000 tHM and less than 10 000 tHM)	China	1 052
	Hungary	1 328
	Slovakia	1 775
	Bulgaria	2 031
	Finland	2 049
	Italy	2 162
	Switzerland	2 616
	Taiwan	3 322
	Belgium	3 476
	Lithuania	3 607
	Argentina	5 328
	Sweden	6 447
	Spain	6 570
	Ukraine	6 926
	India	7 351
C (Greater than 10 000 tHM)	Republic of Korea	10 826
	Germany	13 772
	Russia	19 995
	Japan	27 736
	United Kingdom	40 854
	France	41 490
	Canada	46 836
	United States	60 941
	Total	322 960

Generically speaking, the main considerations used in the concept definition (not necessarily in order of importance) are

- **compatibility** between the host (or accepting) country and the offering countries, from the point of view of matching the needs of the one to those of the other
- **commonality** in terms of sharing wherever feasible, common facilities amongst the participants. This would be particularly relevant to complex and expensive systems such as storage, conditioning plants and repositories.

264

- **proximity** of participants within a geographical sense, ensuring that transboundary transportation of HLW/SNF amongst participants is minimised as far as possible . This implies that these countries should preferably, but not necessarily, fall within the same region of the world.
- **sovereignty** of the participating countries, as regards the use of their respective territories for the purpose of carrying out international waste management activities. Institutional control over SNF/HLW activities should never overlap between participating countries
- **durability** of the agreements on which the undertakings of the participants are based
- **accountability** of the participants for liabilities incurred

The international HLW/SNF management system is defined in terms of the following aspects, i.e., the basic elements of the system, the responsibilities of the main players within the system, and the organisational and structural aspects of the system.

4.1. Basic Elements of the System

Waste inventory: Identification of existing and anticipated radioactive waste available from the participating countries, including amounts, location, radio nuclide content, and other physical and chemical characteristics,

Protection objectives: definition of a rational set of safety, radiological and environmental protection objectives, from which standards and criteria are derived within the respective regulatory systems of participating countries

Management system: establishment of a system for organising the various waste management activities amongst participants

Resource requirements: provision for a funding structure and the allocation of resources essential for the management of the participants' radioactive waste

4.2. Responsibilities of the Main Players within the System

The responsibilities of the various role players within a typical national waste management system are defined in Fig. 2. The above system is based on the recommendations of the IAEA for national waste management systems [5] and clearly distinguishes between the responsibilities of the *State,* the *Regulatory Body* and the *Waste Generators* and *Operators.* The system outlined in Fig. 2 thus applies to both the host country accepting and the offering countries transferring the HLW/SNF.

4.3. Organisational and Structural Aspects of an International Radioactive Waste Management System

Having thus defined a typical national SNF/HLW management system in general terms, the interactive process between two (or more) independent national management systems can be examined within the context of a common international waste management system.

Where SNF/HLW is transferred from one country to another, two independent national systems interact with one another, as shown in Fig. 3. It is important to note that each country, within such a comprehensive interactive system, maintains full institutional control of its SNF/HLW as long as the wastes remain within a country's national borders. The national regulatory regime thus fully applies within each country, to the exclusion of any other regulatory regime, on the basis of national sovereignty.

Establish a Legal
Framework
and provide
Adequate Resources

PUBLIC AUTHORITIES

LEGISLATURE

GOVERNMENT

Establish a Regulatory Body

REGULATOR

Advise Government

Define
Responsibilities
of Generators

Define Responsibilities of
Operators

Enforce Legal Requirements
Implement Licensing Process

WASTE
GENERATORS

Contractual
Relationship*

WASTE
OPERATORS

-      Comply with legal requirements
-      Manage HLW/SNF safely
-      Comply with legal requirements

-      Identify an acceptable destination for HLW/SNF
-      Manage HLW/SNF safely
-      Comply with legal requirements

*The IAEA management system does not clearly
differentiate between generators and operators, a
distinction that is vital to this concept.

The different responsibilities shown in this
diagramme are taken from the IAEA National
System for Radioactive Waste Management

FIG. 2. National system for HLW/SNF management.
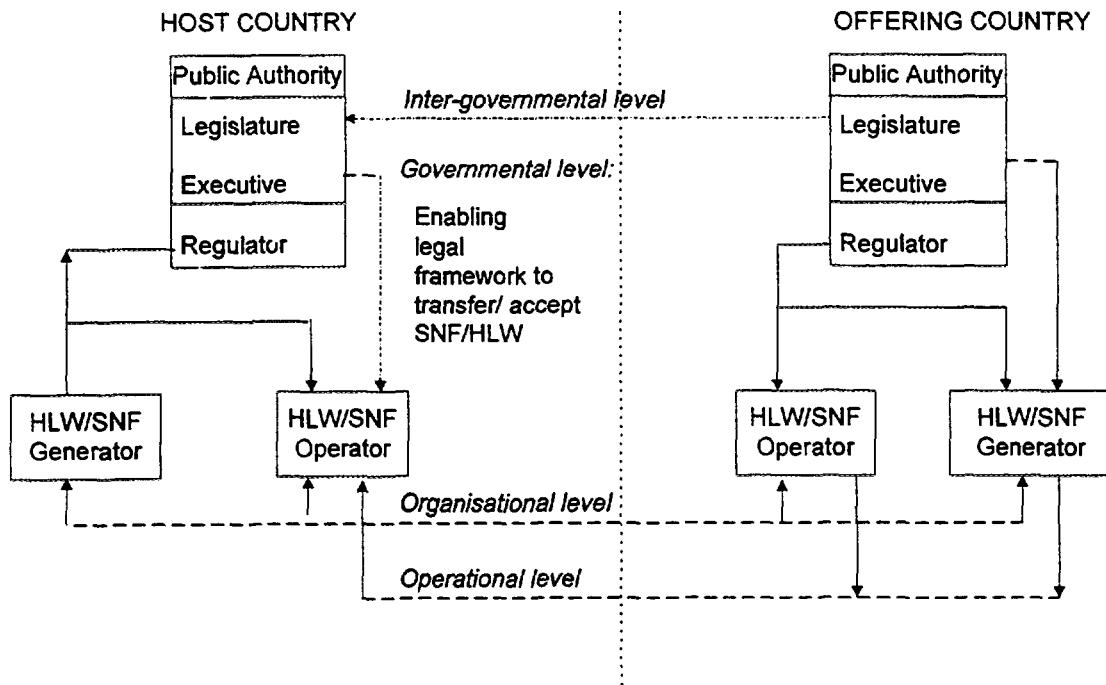
Third party countries may also be involved in the host/offering country relationship, e.g. countries through
whose territory SNF/HLW is transported or countries bordering on the host country. Third party country
involvement may entail joint Public Authority and Operator arrangements

FIG. 3. Interaction between two or more independent HLW/SNF management systems.

266

The contact between two of more independent national systems take place at four different levels:

- *inter-governmental level*: international agreements, such as treaties and conventions are entered into as a means of constructing an overall umbrella for national organisations, in order to negotiate multi-lateral agreements

- *the governmental level*: host and offering countries, as well as third party countries, where applicable, each promulgates enabling national legislation in support of such inter-governmental agreements, in order to give the necessary permanence and continuity to the undertaking

- *the organisational level*: generators and operators of waste in host and offering countries respectively, as well as in third party countries, where applicable, agree contractually on the terms of the waste transfer among themselves. Such agreements are ratified/endorsed by the abovementioned intergovernmental agreements, and in addition, said agreements have to comply with national statutory requirements

- *the operational level*: the necessary safety requirements pertaining to transboundary transfer of HLW/SNF have to be satisfied. Reference to the relevant treaties, conventions and other regulations governing such transboundary movements is necessary.

5. EVALUATION OF THE INTERNATIONAL HLW/SNF MANAGEMENT CONCEPT

The evaluation process below is carried out in terms of a technical, economic, institutional and ethical analysis.

Technical and safety: all repositories, regardless whether they operate at national or international level, have to comply in any event with similar protection objectives, that is, similar safety principles, technical standard and licensing criteria. No inherent difficulties are foreseen at the technical level for an international management system, in fact, cooperation on technical aspects, among participating countries, may significantly enhance repository safety.

Economic and financial: enhanced economy of scale in waste management facility construction and operation is an obvious advantage offered by the international system. The financing of the international system will be influenced by the problems inherent in the long time scales involved. For example, the funds for waste management are accumulated during the electricity generation phase and typically spent over an extended period until the waste is finally disposed of. Difficulties are not foreseen regarding the financing of the scheme provided the special circumstances referred to above are taken into account.

Institutional: the legal, safeguards and regulatory aspects are not considered to pose a serious problem, since the regulatory systems of the participating countries are unaffected by virtue of national sovereignty and will apply exclusively within their own territories during the transfer of the waste. Ownership will finally rest with the host country.

Ethical: the IAEA safety principles - especially the protection of human health and the environment, the protection beyond national borders, the protection of future generations and limiting the burden on future generations - constitute a set of standards, which, when complied with by participants in an international system, should satisfy ethical concerns.

6. POTENTIAL BENEFITS OF AN INTERNATIONAL WASTE MANAGEMENT SYSTEM

It is recognised that various conditions have to be satisfied before an international waste management system can be established. The opportunities that could potentially flow from the

implementation of an international system are very attractive. These opportunities, as well as other potential benefits, can briefly be summarised as follows:

- Potential improvement of safety standards due to the sharing of natural, technical and economic resources;

- Enhanced cooperation on waste management research and development projects amongst host and offering countries, i.e., sharing of development and evaluation costs and fostering of closer cooperation between offering and host countries in solving generic radioactive waste management problems;

- Enhanced economy of scale in waste management facility (including repository) construction when carried out on an international basis, i.e., reducing unit cost by disposing of larger quantities of waste within the same repository, for example, albeit that such quantities are limited in volume;

- Greater standardisation between different national waste management systems, in general resulting in compatibility and consequent cost reduction of waste management facilities;

- Easier access to frontend and backend technology by host countries wishing to establish a comprehensive domestic nuclear fuel cycle, linked to an international disposal system;

- Reducing the number of national HLW/SNF repositories worldwide; thus enhancing safety, reducing the burden on the environment and permitting better institutional control of repositories;

- Potential improvement in the public perception of civilian nuclear power programmes, by facilitating an internationally acceptable solution for HLW/SNF disposal;

- Serving as encouragement to countries that contemplate the introduction of nuclear power, but which countries are currently unable or unwilling to develop a dedicated domestic backend programme;

- Assisting the international nuclear power industry in seeking a permanent solution to one of the most important outstanding problems of nuclear power, i.e., the resolution of the problem of final disposal of HLW/SNF;

- Requiring no additional safety features for an international repository, as similar studies, evaluations, assessments and licensing procedures are required for both national and international repositories;

7. TYPICAL PROFILES OF HOST AND OFFERING COUNTRIES

Typical profiles can be defined for potential host and offering countries. These serve, in the case of countries wishing to participate in an international waste management system as an indication of the criteria that should typically be satisfied at the national level.

7.1. Potential Host Countries

Countries having certain attributes that are considered necessary, but not essential, to act as potential hosts for the transfer of radioactive material from offering countries, are typically those

- with a well developed domestic nuclear expertise and infrastructure in terms of radioactive waste handling, treatment, transport, storage and disposal facilities

-        with licenced (or at least potentially licenced) radioactive waste storage and disposal sites

-        with a well developed institutional, i.e., organisational, legal and financial framework for radioactive waste management

-        having the intention to act as the sole authorities in charge of licensing, inspection, verification of operations, and the establishment of the rules for post-closure control of the repository

-        being prepared to accept responsibility and liability for any possible future interventions, relating to transferred radioactive waste

-        having a reasonable level of public acceptance of nuclear power in general, and radioactive waste management in particular

-        having signed the NPT and applying IAEA safeguards to their nuclear facilities, as well as being a signatory to other relevant international conventions

-        having the necessary technical, economic, organisational and financial resources to effectively host a regional repository.

7.2.   Potential Offering Countries

Countries with attributes, considered necessary, but not essential, to act as offering countries, are typically those

-        having limited nuclear programmes, generating small quantities of radioactive waste;

-        lacking the capability for establishing a cost effective disposal facility, on the basis of limited quantities of radioactive waste (lack of economy of scale);

-        lacking suitable geological formations for final disposal purposes.

8.   CONCLUSIONS

The safety and economic benefits that could potentially flow from the implementation of an international repository are very attractive in terms of

-        improved safety standards due to the sharing of natural, technical and economic resources

-        reduction in the number of national HLW/SNF repositories worldwide; enhancing safety, reducing the burden on the environment and permitting better institutional control of repositories

-        enhanced economy of scale in waste management facility (including repository) construction when carried out on an international basis, i.e., reducing unit cost by disposing of larger quantities of waste within the same repository

However, ethical issues, including public perception, are considered potentially to be the most challenging aspect of the international HLW/SNF management concept. The perception that future generations may be burdened with the management of radioactive wastes arising from the present generation needs to be addressed. Sufficient institutional guarantees have to be provided to cover all liabilities associated with the future management of the present generation's radioactive waste.

In conclusion, it appears to be entirely feasible for a group of countries, each of which is generating HLW/SNF in such quantities as to render individual domestic HLW/SNF disposal facilities unrealistic, to dispose of this material in a common, safe and viable disposal facility, provided by one of the participating countries.

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INTERNATIONALIZATION OF THE BACK END OF
THE NUCLEAR FUEL CYCLE: PROBLEMS AND PROSPECTS

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Abstract

International cooperation and transnational division of labour is a distinctive feature of the nuclear industry, but it is conspicuously lacking at the back end of the nuclear fuel cycle. Meanwhile, national efforts to close the fuel cycle have remained largely unsuccessful. Governments and the nuclear industry are paralyzed in a gridlock of indecision and obstruction. This pattern has been reinforced at the international level. More recently, however, a number of dynamic challenges to governments and the industry has opened up new prospects for internationalization.

1. INTRODUCTION

Internationalization has been a distinctive feature of peaceful nuclear activities since the beginning of the Atomic Age. From the Baruch Plan downward, internationalization was regarded not only as a preventive measure against weapons proliferation but also as a positive support for the spread and development of nuclear power utilization. This expectation has largely become true. The nuclear industry is characterized today almost everywhere by a high degree of international cooperation and transnational division of labour, ranging from research and development to reactor building, ownership and operation, from safeguards to safety standards, from electricity generation and distribution to finance and insurance. Joint undertakings, shared responsibilities and interdependent activities cutting across national boundaries have been a well-established practice of the nuclear industry for many years, often supported and regulated by intergovernmental agreements.

Remarkably, though, such cooperative achievements are virtually absent at the back end of the fuel cycle where the final disposition and disposal of spent fuel and radioactive material is concerned. Here only national solutions to problems of individual countries are being actively pursued, although none has advanced very far. At the same time, tentative exploration of various schemes of internationalization has regularly foundered at an early stage. The historical record of the past decades is littered with the acronyms of defunct proposals for an internationalized back-end fuel cycle: RFCC, INFCE, IPS, ISFM, INWAC, IMRSS, to name the most ambitious. Not only have these proposals not materialized; it appears that at the back end of the fuel cycle internationalization is actually on the retreat. Multinational ventures in reprocessing, such as EUROCHEMIC, have been abandoned. Previous commitments by some leading nuclear countries, notably the Soviet Union and the United States, to take back spent fuel from their client countries have been revoked. Exploratory talks with several countries to accept foreign nuclear wastes for burial on their national territory (Argentina, Iran, China, the Soviet Union, among others) have come to nought. Even in those cases where international cooperation seems now to be well under way (with countries like Japan, Germany, Belgium and Switzerland having some of their spent fuel reprocessed in France and Britain), this is only a half-hearted and temporary exercise, pending more permanent national solutions. In addition, final waste disposal remains entirely in the national domain.

All this raises a lot of questions. What are the reasons for the nuclear industry's failure to extend international cooperation to such areas as spent fuel management, waste disposal and plutonium treatment? Which arguments weigh in favour of internationalization, and which factors are working against? How do technical, political, legal, institutional and commercial criteria relate to each other at the back end of the fuel cycle when international arrangements are at stake? How does the civilian and military interface of nuclear technology come into play? For which purposes and under what kind of circumstances is international cooperation most likely to succeed?

2. COMMON PROBLEMS

Why should we expect a process of internationalization at the back end of the fuel cycle? The simplest answer is suggested by the fact that all countries with a nuclear power programme (their number presently stands at 32) have to solve the same problem: What to do with the stream of spent fuel coming out of the nuclear reactors under their jurisdiction. In principle, of course, all 32 countries could individually and separately seek a solution to the problem all of their own and entirely for themselves. This would be a folly, however, for three obvious reasons: it would be useless, because the number of possible solutions is quite limited; it would be uneconomical, because it would forgo the efficiencies that result from an international division of labour; and it would be dangerous, because in many cases a reckless national solution may prejudice the safety and security of neighbouring countries. It is easy to conclude, therefore, that any national fuel cycle policy without a considerable degree of international cooperation is in the end unlikely to succeed.

Yet the fact remains that internationalization is not forthcoming. National solutions are instead being sought and upheld. A recent survey shows that among countries with nuclear power all but a few have chosen for themselves one of two possible approaches: either reprocessing, which most countries seem to prefer, or direct disposal of spent fuel; in a few countries, a combination of both approaches is also envisaged[1]. At the same time, however, not one country has actually consummated its avowed fuel cycle strategy. Some appear to be on their way, although with considerable delays as compared to original schedules. Others have run into technical, administrative or legal difficulties which brought implementation of their programmes effectively to a halt. Most countries have deferred their decision and postponed definitive commitment to a specific fuel cycle scheme. As a result, the prevailing pattern is for spent fuel to be kept in cooling ponds and interim storage, with some plutonium having been separated and recycled. High level waste has not reached a final repository anywhere.

In other words: While little or no progress has been made on the international level to resolve the back-end problems of the fuel cycle, little or no progress has been made on the national level, too. Stalemate and procrastination seems to be a general phenomenon of fuel cycle policy everywhere. This calls for a closer look at causes and effects, and at the interrelationship between the two levels. A popular presumption seems to be that internationalization cannot take place before national programmes are firmly assured. But this may be the wrong way of looking and reasoning. Possibly it is the premature assurance of programmes which stifles progress on the national as well as on the international level.

3. THE GRIDLOCK OF NATIONAL FUEL CYCLE POLICY

In many countries with nuclear power the survival of the industry is threatened by a peculiar double-bind situation. Popular resistance, media attention, legal action and regulatory requirements, all of which used to impede the construction of power plants for many years, are now focussed mainly upon the back end of the fuel cycle. Anti-nuclear sentiment has turned more and more away from operating reactors towards the issues of spent fuel storage and transport, plutonium use and waste disposal. While nuclear electricity generation has gained some reputation as a smoothly running business the industry, in the absence of a closed fuel cycle, is accused of operating irresponsibly „like an airplane that has taken off without a landing strip in sight". The accusation is not entirely unfounded. After all, the closing of the fuel cycle, scheduled in some previous projections to be completed by the 1980s, has not yet happened a decade later and is, indeed, today farther away than at any time before. As a result, and in anticipation of anti-nuclear arguments, governments and regulatory agencies together with the nuclear industry itself have gone out of their way to assure the public that there is nothing to worry about. The landing strip for the nuclear airplane, as it were, is promised to be under construction. Typically, national governments have underwritten this promise, taking upon themselves the responsibility to guarantee its fulfillment. The

nuclear industry in individual countries is under the legal obligation to provide for the safe disposition of spent fuel and the final disposal of radioactive waste. In some countries this obligation is directly tied to the operating license for power plants. Nuclear electricity generation must be shut off if a judicial court finds assurance of the legal obligation to be lacking. In this way, the back end of the fuel cycle has come to be the most vulnerable spot of the nuclear industry in many countries.

The dilemma resulting from this situation is twofold. National governments and the nuclear industry are locked with each other in an uneasy alliance, seeking to obtain the same objective, the credible assurance of a closed fuel cycle, while trying not to become altogether dependent on each other. The industry, which in many countries is not strictly speaking a nuclear industry but a mixed bag of commercial enterprises, mostly electric utility companies with business activities beyond nuclear power alone, is primarily interested in a dependable return on investment for the lifetime of their nuclear plant. Their choice of fuel cycle strategy is determined by technical feasibility, commercial profitability and the set of rules and regulations defined by the respective government. Governments, on the other hand (at least in democratic societies, which is today the case almost throughout the nuclear group of countries), are primarily interested in political legitimacy, support and stability within their respective constituencies. Their choice of fuel cycle strategy is determined by public opinion and popular sentiment, constitutional and institutional setting, partisan politics and electoral expectations.

The interaction of governmental and industrial interests has resulted in three characteristic effects on back-end fuel cycle policy everywhere. First, a strong preference for separate and independent national policy choices has been established. As they are confronted with domestic anti-nuclear opposition, governments opt for and hold fast to what they believe to yield the optimal political pay-off within their own territorial constituencies. Structural contingencies reaching across national borders count as a liability rather than an asset in such a calculation. Thus, in an automatic and almost inevitable reflex of institutional self-interest, governments tend to refuse having foreign nuclear wastes located on or near their own territory, and in some cases actively encourage wastes originating from their own territory to be shipped abroad.

In federal systems (like the United States, Germany, Switzerland, and presumably Russia in the years to come) this pattern is repeated on the subnational level of territorial units (states, Länder, cantons, autonomous republics or regions), resulting in a complicated vertical and horizontal trade-off of interests between competing governments. When national governments, for obvious reasons, refuse to accept foreign nuclear waste on or near their own territory („not in my back yard", as the saying goes, or NIMBY for short), they imply as a matter of fact that the nation-state is the appropriate authority to define the legitimate territorial dimension for nuclear waste disposition. Such a claim is openly challenged, however, in those federal systems where sub-national governments refuse, in the true spirit of NIMBYism, to accept on their soil spent fuel or waste from other parts of the national territory. There is an obvious lesson to learn from this: It is the territorial dimension of political legitimacy which makes the problem of nuclear waste so difficult to resolve. Someone's back yard is always another one's front porch.

The self-reference of territorial politics in the nuclear field has traditionally been reinforced by industrial interests. The nuclear industry, being used for historical reasons to an extraordinary degree of governmental guidance, supervision and regulation, has tended to accept quite readily the national framework of political tutelage. Nuclear reactor development and construction benefited for a long time from public subsidies as a measure of national industrial policy. Electric utility companies, mostly state-owned until quite recently, have enjoyed for many years the benefits of legalized monopoly status and state-controlled price stability for their product. Electricity generation is traditionally associated with a business culture more like a public service than a competitive enterprise. Nuclear electricity generation in the face of popular opposition is totally dependent on government protection and support. Consequently the nuclear industry grew up everywhere in a close

symbiosis with national governments and has managed to survive and flourish only in those countries where national governments persisted in their support.

Government support cannot, however, guarantee the smooth functioning of industrial activities. At the back end of the fuel cycle, industrial projects such as reprocessing and waste disposal have collapsed because national governments could not prevail in the political process (this is a typical situation in federal systems) or because they raised regulatory standards so high as to make the projects uneconomical for the industry. In both cases the nuclear industry may find itself in a gridlock of conflicting interests and commitments from which it is difficult to extricate itself. Governments, on the other hand, tend to arrogate for themselves an industrial leadership role in nuclear affairs which may overstrain their capacity for effective problem-solving.

The latter point is most obvious where nuclear waste disposal is concerned. Taking their cue from reactor safety standards, where it makes good sense to require infinitesimal risk margins to be achieved, governments have lapsed into the false analogy to require similar risk margins for spent fuel and waste management. Hence, political and legal commitments are entered into which claim to be valid for more than the half-life of harmful nuclear fission products, i.e., for thousands of years. The idea is, of course, to create trust and confidence in the public at large and thereby lay a solid and dependable foundation for the operation of national nuclear industries.

The opposite may result, however. Anti-nuclear critics are right to scorn such unlimited commitments and to point fingers at the gross incongruity of national fuel cycle policies which claim to be made for eternity but are, in fact, being changed and reversed ever so often before everybody's eyes. Governments expose themselves to ridicule when they pretend to take adequate precautions for the well-being of hundreds of future generations at the same time as they find it difficult to provide adequately for the living. The pretense of caring for a distant future is often proof of a failure to handle more immediate tasks.

In considerations about back-end nuclear fuel cycle policy the standards of scientific, ethical and practical reasoning have become warped and garbled in a peculiar way. It is a folly to promise assurance of safety and security in a uniform fashion for the lifetime of nuclear installations regardless of whether this extends over a few decades (as with power reactors) or over a period of time far beyond any human experience (as with spent fuel, plutonium and high-active waste). On a technical level the latter is, in fact, far less demanding than the former. What is a stake, however, is not really the solution to a technical problem but the discharge of a political responsibility. Technical solutions may endure for an infinite time; political responsibilities can be honored only for very limited periods. Any back-end fuel cycle scheme, whatever its technical specifics, can be assured politically only for a very limited period. If more is promised, the promise itself will undermine the creditability and legitimacy for which it was made.

The basic argument here is this. Political institutions, including sovereign nation-states, are notoriously short-lived, fragile and unstable. They are historical creatures with an in-built tendency towards failure and decay. A responsible fuel cycle policy cannot be predicated on the longevity of nation-states. While their individual half-life cannot be established in advance, historical experience suggests it to be on the average quite brief. Two-thirds of the United Nations' present membership was not yet in existence when the first atomic chain reaction was accomplished. In the past 20 years alone, several dozens of states were affected by revolutionary upheaval, the breakdown of law and order, collective violence, civil war, separatism and territorial disintegration - including one in every two states with nuclear power plants. Ironically, among those which broke apart more recently there was a significant number of states which had subscribed to an official ideology predicting the „withering away of the state" as a consequence of social progress. Whatever the twists and jerks of social progress, they should better not be allowed to define the optimum of fuel cycle management at any given time.

Nuclear energy is all too often associated with an elevated mystique of time and space. A more pragmatic approach would search for the mundane treatment which it deserves. Immunity against the unstable nature of political institutions is now mostly sought in technical solutions, such as multi-barrier repositories for nuclear wastes in deep geological formations, which appear to take care for themselves. It would be wrong, however, to expect such technical fixes to work independently of political change. Firstly, for safety and security reasons, they require continuous monitoring over indeterminate periods and, therefore, a certain amount of institutional continuity or adaptation. Secondly, unforeseen kinds of human intrusion (advertant or inadvertant) into a supposedly remote location cannot be excluded forever. What seems to be an ideal geological repository today (salt, granite, tuff, etc.) may turn out to be totally inadequate within a relatively brief period. Who would have expected only a few generations ago, for instance, thousands of deep boreholes being brought down in the Arabian peninsula, the North Sea, Alaska or Siberia in search of oil and gas?

It follows that any responsible long-term scheme must not ignore or deny the fragility of political institutions, of nations-states and of international relations, but must accept it as a given fact. What is needed for the back end of the fuel cycle is, therefore, a kind of provisional assurance to remain reversible, flexible and adaptable under the most unlikely circumstances of political change.

4.   NEGATIVE INTERNATIONALIZATION

National preoccupation with national problems in a national framework of interests is the major reason for the nuclear industry's failure to reach beyond national boundaries at the back end of the fuel cycle. But it would be wrong to see this as the only reason. National policies are not made in isolation from other countries or in disregard of foreign relations - in the nuclear field even less than in other fields. What can be observed is in fact a high degree of international coordination and a remarkable amount of international rules and regulations stretching across the whole range of nuclear policy. International policy-making is not absent at the back end of the fuel cycle. It is there, but with a paradoxical result. It does not stimulate transnational cooperation but tends to stifle it; and instead of overcoming national segmentation it tends to reinforce it. It reflects what might be called negative internationalization.

Negative internationalization is caused by the deliberate effort of the world community of states to emphasize the sole and exclusive responsibility of states for all nuclear matters. The non-proliferation regime is the most prominent and powerful expression of this effort, imposing upon national governments the obligation to account for and hold under their sovereign sway everything that has to do with nuclear materials on their territory. It implies a strict separation between nuclear and non-nuclear materials and between civil and military uses. Other international conventions have reaffirmed the responsibility of national governments for nuclear matters such as technical safety, physical security, transportation, civil liability, radiation protection and so on. All of these international agreements impinge on the back end of the fuel cycle in one way or another, and some deal with it explicitly, such as the Antarctic Treaty, the Basel Convention, the London Dumping Convention and the recently concluded Draft Convention on the Safety of Spent Fuel Management and Radioactive Waste Management.

Non of these international agreements prohibits international cooperation; most of them are in fact expressly in favour of it. And yet, their practical and cumulative effect is different. National governments are encouraged to keep everything nuclear under their control, simply because this is the acknowledged and routinely established practice; whereas internationalized schemes of any kind require explicit and complicated efforts to bring them in line with existing legal commitments. Nuclear industrial enterprises have little leeway and few incentives to drive forward across national boundaries on their own without governmental prodding and support. Some possible paths of waste disposal in the global commons are explicitly foreclosed by international conventions, such as deep

sea dumping or burial in Antarctica. Others are strongly discouraged for nonproliferation reasons, such as reprocessing, which is under international strictures from the U.S. Government.

International organizations and multilateral legal instruments reinforce the tendency for national governments to commit themselves for infinite time periods when it comes to nuclear safety issues on their respective home territory. At the same time, exploration of the possible benefits of shared responsibilities is implicitly discouraged. Under the questionable trademark of „sustainability", there is a hallowed preference for the territorial status quo in waste policies (nuclear and non-nuclear), with primary approval being given to waste deposit in the country of origin. In a globalized economy, however, there is no reason why some countries should not make use of their comparative advantage in international trade by accepting the waste of other countries, provided of course that international safety standards are assured.

The legal and political situation is such that most governments will find it convenient and tempting to avoid any engagements in internationalization; instead, they are likely to stick to a strategy of wait-and-see and, in effect, do nothing. If some countries should decide to go forward with more ambitious plans of their own, they may well encounter resistance from an international alliance of sorts. Many governments are outright hostile when it comes to spent fuel from abroad passing through their territory or waste being stored near their borders. Opposition against such plans is particularly vehement, of course, among anti-nuclear groups. It is ironic to note that some of these groups, like Greenpeace, are now organized on the international level more effectively than any governmental or industrial coalition. The masterful campaign by Greenpeace against the Brent Spar deep sea dumping project in 1995 is a case to remember.[2]

International organizations like the IAEA or the EU, should not be expected to take the initiative or give significant momentum to internationalized fuel cycle projects. Such organizations are not well suited to exercise industrial leadership, they are too much under the influence of national governments and confined by legal restrictions to overcome the inertia of established practices. In the case of the EU where the free flow of nuclear goods and services among member countries was agreed to in principle many years ago, it has not even been possible to do away with the resistance of some governments against transborder movements of spent fuel. And yet, it is clear that these organizations are indispensable to define and uphold the regulatory framework without which no nuclear cooperation could survive.

5.   PROSPECTS FOR CHANGE

Neither governments nor international organizations are likely to bring about significant progress towards internationalization of the back end of the fuel cycle. Nor is the nuclear industry likely by itself as long as it remains under the spell of national governments. But change there will be, and it can be expected to contribute to internationalization in a variety of ways.

Several of the seemingly persistent conditions under which the nuclear industry used to operate are in the process of breaking down. The previously sacrosanct separation of civilian and military fuel cycles appears increasingly questionable. Since an outrageous amount of health, safety and environmental malpractice has been uncovered in the military facilities of nuclear weapon states there is growing pressure from governments and public opinion worldwide to bring the management of military fuel cycles in line with the accepted standards of civilian nuclear facilities.

The urgent task of reducing the amount of excess weapons plutonium in nuclear weapon states has far-reaching implications for back-end fuel cycle strategies in these countries and elsewhere. As the task cannot be accomplished within a reasonable time, particularly in Russia, without extensive international cooperation, nation industrial activities will have to be readjusted and harmonized at least between the cooperating countries to accommodate for the additional streams of nuclear material originating in the military sector. It should be noted that this is essentially an

industrial task which requires official approval and support but cannot successfully be devised, financed and managed except on a commercial basis.

Whatever the formal organization and the technical specifics of an international cooperative undertaking for weapons plutonium might be (whether thermal recycling, underground burial, breeder development or what else), they would inevitably affect the structure, timing and economics of national fuel cycle strategies in participating countries. If the blockage in national spent fuel processing continued to be in effect in many countries, resulting in a rapid accumulation of inventories in temporary storage, this might add up to an increased necessity for nuclear power plant managers to seek an outlet in foreign or international spent fuel services. Much will depend on whether or not such services are available in due time at prices that are affordable for nuclear operators.

Economic considerations are likely to play a more prominent role in determining future fuel cycle choices. Previous cost calculations for spent fuel treatment and waste disposal are more and more being called into question as implementation of national programmes is stalled by indecision and postponement. In some countries utility companies are beginning to balk at mandatory contributions to reserve funds which are set aside for the financing of nuclear waste repositories, because time schedules have become obsolete and costs unpredictable. Utility companies themselves are changing, and are finding themselves in a changed environment. Privatization and deregulation programmes in many countries are gradually taking hold. Utility companies, mostly for the first time, are being projected into the role of competitive enterprises in liberalized electricity markets. It is by no means certain whether nuclear power, with all that regulatory baggage on its back, can easily survive under such conditions.[3] More and more utility companies are now responding to the challenge by forging international alliances and trying to capture foreign markets through direct investment, mergers and acquisitions. This is a trend that may undermine the reasoning which has until now favoured national solutions to problems of the nuclear fuel cycle's back end.

The trend is particularly visible in Europe. If European integration moves forward and the internal market for electricity finally becomes a reality, there is a reasonable prospect that it will in the end encompass the whole range of the nuclear fuel cycle, including waste. This could become even more important when Eastern European countries, where the spent fuel problem is already a serious burden for nuclear power, join the European Union. Many years after its foundation the European Atomic Community might then eventually fulfill its early promise.

6.   A LOOK AHEAD

If the nuclear industry is deadlocked in national systems of indecision about back-end nuclear fuel cycle policy, ways should be sought out of the predicament. Internationalization may be an adequate way as well as an appropriate end in itself. The concept of internationalization does not prescribe a definitive structure; it is simply a paraphrase to include all forms of industrial collaboration and division of labour across national boundaries. In contrast to the historical pattern, where international cooperation was typically engineered by governments and international organizations, it will henceforth have to come mainly from industrial interests. Governmental actors should not be expected to take the lead, but they should be urged not to stand in the way of more dynamic industrial initiatives.

In this vein, what could be done to improve international collaboration? First, priorities should be set and problems identified which are more urgent than others and at the same time most rewarding in terms of international pay-off. One of these is surely the problem of excess weapons plutonium in Russia. Others include the problem of spent fuel management in Europe, the region where countries with nuclear power are heavily concentrated, and perhaps East Asia, the region where the growth of nuclear power is now more rapid than elsewhere.

Second, projects should be pursued which can come to fruition and prove their merits within a relatively short time. Collaborative efforts should focus not on an indeterminate future beyond everyone's horizon but instead on tasks which can be fulfilled to the benefit of currently living generations.

Third, internationalization should be sought on a modest scale with limited objectives, preferably building upon existing structures with proven value. Grandiose schemes with global aspirations, starting from the bottom to reach the blue sky, should be avoided; they are bound to fail. Instead, competing projects with different designs should be put to the test in various settings.

Fourth, irreversible decisions and irremediable commitments should be avoided. Flexibility, resilience and adaptability are of the essence. Internationalized schemes should be open to experimentation and must be able to learn from experience and failures.

Fifth, international projects, in order to endure and persist, should not be dependent on subsidies and contributions. They should be self-sufficient and possibly profitable, operating as an enterprise and not like a bureaucracy. Participants in such a joint project should collaborate out of self-interest rather than a legal obligation.

Is there a role for an international organization like the IAEA in the creation of such enterprises? Not in the sense of some superior authority or direct managerial function, as was originally envisaged in the Agency's statute and several subsequent projects dealing with spent fuel and plutonium. But the IAEA could lay the foundation for such enterprises by defining the minimum of necessary rules, stimulating discussion, encouraging initiatives and providing legitimacy for innovative projects of industrial internationalization.

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CLOSING THE FUEL CYCLE - REACHING A PUBLIC CONSENSUS

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Abstract

There are three reasons for wanting nuclear power: it does not produce air pollution, or add to global warming; and it is effectively sustainable. What priority is attached to them? Is the possibility of alternate fuels being developed in the next 20 years large enough that mankind can afford not to develop the nuclear option as a possibility? Is the breeder reactor really needed, and when is the earliest time? Was the NAS 1994 (Panofsky) committee right that the existence of excess weapons plutonium present is a clear and present danger to the USA? If so how can we persuade the President to act? Is there a clear and present danger to other countries too? If so why are they still waiting for the U.S. to act? What are the true economic costs of reprocessing using the present PUREX process and can they be brought down? Is the extra cost of disposing of whole fuel rods vs separated waste, more or less than this? What, if any, is the difference (such as heat from Pu^{238}) between the ease of using "reactor grade" plutonium and "weapons grade" plutonium to make an atomic bomb? Can the difference be increased, and can this difference (if any) be translated into a lower cost for protection of or greater public acceptance of reactor grade plutonium? What could be an international research effort for a better fuel cycle? e.g: Introducing an IFR fuel cycle into Beloyarsk, Monju and/or Phoenix? Introducing a thorium cycle? Has anyone carefully Recorded, Understood and Explained the past history of breeder reactor technology both of accidents, and of failures and successes? If so, where is it? If not, why not? Is the report by Clarke of NRPB in UK on plutonium toxicity that belies the claim that it is unusually toxic widely known? If not, why not? Can the MAYAK experience with misuse of plutonium be used to help in public understanding? Since India and Pakistan will not sign NPT, can more imaginative, quiet, talks with Indian and Pakistani leaders persuade them to come to a non-nuclear agreement on their own which would satisfy the rest of the world?

1. INTRODUCTION

Fermi's Dream and Ford Foundation's Nightmare.

Before 1975 there were coherent and widely accepted plans for a nuclear fuel cycle in the world which for brevity I will call Fermi's dream. One starts from uranium ore, processing it to form uranium metal, burning the uranium 235 in an electric power producing reactor, reprocessing the fuel to separate the uranium 235 and plutonium 239 for use in fast neutron reactors. All that would be left for subsequent waste disposal would be fission products themselves, almost all with half lives of 30 years or less. The fast neutron reactor of preference was cooled with liquid sodium.

In the early 1970s problems appeared in the Fermi dream. It was realized that the existence of many tons of chemically separated plutonium might lead to a possibility of theft, or "diversion", of enough material to make a nuclear bomb. A study sponsored by the Ford Foundation (Keeny et al., 1977) led to a decision of President Carter on April 7th 1977 to abandon the plans in the U.S. to reprocess spent nuclear fuel, and slow the development of the breeder reactor - a policy followed by the present U.S. administration. On the one hand, Keeny et al. argued that by refraining from reprocessing the U.S. was setting an example to the rest of the world and indicating that the U.S. believed that a breeder reactor is not necessary. On the other hand there are a few in the U.S. who suggest that the US should immediately begin to reprocess fuel again.

This subject interested Andrei Dmitreyvich Sakharov while he was alive. He was an optimist, yet a realist. He insisted that human rights without human (technological) progress was not possible,

since freedom from want could not be achieved. Yet technological progress without attention to human rights and liberty leads to a failure to manage the technology, with disasters such as occurred at Chernobyl and Bhopal. Andrei Sakharov also argued that on technological matters of public importance scientists without a government position should discuss the issues and recommend actions.

2. WHAT ARE THE REASONS FOR WANTING NUCLEAR POWER?

There are three basic reasons why environmentalists should be strongly interested in advancing nuclear power:

(1) The major alternate to nuclear power is the burning of coal which inevitably produces air pollution. Many scientists believe that nuclear power in ordinary operation has no important pollutant emissions, fine (probably acid) particles still cause premature death for 70,000 people a year in the USA and proportionately elsewhere (Shprentz, Bryner and Shprentz 1996, Wilson and Spengler 1996).

(2) The burning of any fossil fuel produces carbon dioxide, which probably changes the earth's greenhouse, and may induce major climate change. This has been advertised by the present Vice President of the U.S. A. (Gore, 1990). At the Rio de Janeiro in 1991 and in Berlin in 1995 the world's politicians agreed to cap the greenhouse gas emissions and study further reductions in emissions. Three leading scientists with contrasting opinions on the reliability of the scientific data, nonetheless called for use of alternates to fossil fuels when economically feasible (Singer, Revelle, and Starr 1991).

(3) One long-term requirement of any energy system is its sustainability. Fermi's dream of a breeder reactor clearly encompassed this goal. No other energy source presently can guarantee energy supplies at a known modest cost for a long time. Pietr Kapitza and Sakharov both discussed this (Kapitza, 1970; Sakharov, 1978), and Sakharov discussed it again at the historic Conference on a Nuclear Free World in Moscow in February 1987.

The first set of questions that I ask is:

How well known are these three reasons, how well are they accepted, acknowledged and what priority is attached to them? (particularly by those opposed to expansion of nuclear electric power)

These reasons have not yet been driving forces for expansion of the role of nuclear powered electricity. Even though the role of nuclear electric power is still expanding in some countries, it seems that other negative thoughts about nuclear power overshadow these three reasons in many people's minds, and in the "trade-off" which each individual, organization and government must make, nuclear electric power has suffered in many other countries. In particular, there many people seem to hope that alternative energy sources to fossil fuel and nuclear power will become economically viable in the next decade or two. Therefore it is vital to understand what these other negative thoughts are, and to determine whether and how they can be made to be less significant.

3. ALTERNATIVES FOR AN ENERGY FUTURE

Before 1973 in OECD countries, and in the USSR, the cost of fuels, and electricity, was continually declining in real terms. This led to what would now be termed wasteful practices, and what would now seem to be an excessive demand for new electricity generating stations. Since 1973, the total energy per capita has stayed constant or declined, although electricity use has continued to rise. This has led many analysts to believe that more efficient end use can lead to further reductions in fuel use in OECD countries, and can slow the rise in developing countries.

Is the possibility of alternates being developed in the next 20 years large enough that mankind can afford not to develop the nuclear option as a possibility?

Even if one accepts the aforementioned reasons for developing nuclear power, the increase in availability of uranium (and for a few years the burning of plutonium released from weapons stockpiles) can delay the need for using the full energy potential of the uranium fuel. The urgency in developing a commercial breeder reactor that was felt by many experts in 1970 can be replaced by a sense that there is time "to do the job right." But an urgent question still remains:

Are there reasonable scenarios that demand the development of the breeder reactor on a rapid time scale?

A concern of many experts in the 1970s was that nuclear electric power was expanding at an unprecedented rate for an energy technology, (as described for example in papers by Cesare Marchetti) and that a slower, more deliberate, pace would be beneficial. We can still ask:

What is an optimum pace for development of a breeder reactor technology and does that match reasonable scenarios for the demand?

The program for the fuel cycle then should be different from that envisaged in 1970, or even at the International Fuel Cycle Evaluation (INFCE) in 1980. There is time - perhaps as much as 40 years - to experiment and learn how to make the fuel cycle acceptable to a broader group of people. The arguments that nuclear power advocates should make to their peoples and their governments are also different. No longer should they argue an urgent need; but neither should they accept that there exists a *known* alternative to breeding nuclear fuel to satisfy the environmental demands. They can be more general: the cost of developing an option for the future that may eventually be discarded (if the optimists are correct) is not great compared with the cost to society of not having a viable option when the time comes. It is important to open up options for ones' grandchildren: not to close them off. Anything else is unsustainable. This demands that the world should continue to spend money on research and development on the breeder reactor option.

We may have 40 years to develop a nuclear power program that includes use of plutonium, that is acceptable to the people. But we do not now have a coherent plan on how to proceed, and I do not believe that we even have a clear statement of the problem that can be generally accepted. Thus I ask both the politicians and the "industry":

What has been accomplished to make an acceptable nuclear program in the 20 years since the Carter decision? Either by the "industry" or by the authors of the Ford Foundation report?

4.   THE PREVENTION OF CLANDESTINE NUCLEAR BOMBS

Many scientists have argued that the only real issue about nuclear power is the connection with weapons (e.g. Cottrell, 1981; Flowers et al., 1975). While this may not be completely true, I assume for the purposes of this discussion that if this issue could be "resolved", the other issues will fade into insignificance.

Before 1990, when the cold war was in progress, the existence of enough weapons plutonium for over 30,000 atomic bombs made the presence of plutonium in electricity producing reactors reactor fuel seem a small problem to many. Yet the Keeny et al. echoed the feelings of several scientists and others that there were inadequate plans in the world to control the plutonium in the civil sector. This feeling has increased now that the cold war is over. The focus of a 1994 U.S. National Academy of Sciences report (Panofsky et al., 1994) was on the disposition of excess weapons plutonium, but much

of the concern follows through to plutonium in nuclear electric power. This was made somewhat clearer in the 1995 report of the American Nuclear Society (Seaborg et al., 1995). The National Academy report called the existence of the excess weapons plutonium "A clear and present danger" to the United States - wording that, if accepted, would demand immediate action from the President. Although this urgency has not been accepted (excess weapons plutonium is clearly less of a danger than the cold war was), most analysts agree that coping with excess weapons plutonium is important. However, the delays in coping with the military problem by the U.S. Administration gives time for the nuclear power community to consider a long term plan for management of plutonium in the civilian nuclear industry. Both the NAS and the ANS reports also emphasized the urgent importance of a secure storage of militarily usable plutonium in an internationally verifiable way - a vital subject that is peripheral to this paper.

Was the NAS 1994 (Panofsky) committee right that there is a clear and present danger to the USA? If so how can we persuade the President to act? Is there a clear and present danger to other countries too? If so why are they still waiting for the U.S. to act?

One of the options for disposing of excess weapons plutonium and ensuring that it will not ever be used for weapons is to burn it in a reactor. This is the only way of actually destroying it, and has therefore a number of psychological advantages. While disagreements remain it is noteworthy that at several public meetings many persons normally opposed to nuclear electric power have agreed that burning plutonium is a good, or even the best, option. If that is decided, and it certainly seems to be the intent of the Russian government to pursue this route, there will be a quantity of plutonium to fuel reactors for a few years. When this is combined with the low price of uranium ore and the existence of an excess of highly enriched uranium, there will be enough fissionable material in the next few years to reduce the urgency for reprocessing, but there will be a shortage of fabrication facilities for mixed oxide fuel.

This then leads to the question:

Should the immediate aims of operating and soon to be operating reprocessing plants be redirected to development aimed at understanding how to make reprocessing cheaper, and safer? and how to explain that to the public?

Instinctively most of us recoil at the idea of burying material that is potentially useful - such as the plutonium with its energy content. The specter of a "plutonium mine" has been raised. After 300 years when most of the fission products will have decayed it would be possible to recover the plutonium without the dangerous barrier of radioactivity. Thus it remains very important to have available the alternate of destroying the plutonium and actinides. While this can be done to a considerable extent by recycle in a slow neutron Light Water Reactor, it is easier and more complete in a fast neutron reactor.

This immediately leads to the question:

What is the cost advantage, either in direct technical costs or in public perception, of removing the long lived material before burial of the nuclear waste?

One of the premises of the Keeny et al., report was that it was technically easy, and not very much more expensive, to dispose of whole fuel rods including the long lived actinides, and not merely the fission products. This leads to the questions:

Is this presumption technically true? and

Why are not the authors of the Keeny report acting to persuade the government to demonstrate this soon by burying fuel rods now?

Plutonium separated from spent fuel is now piling up in many countries. A significant bottleneck is in the limited fabrication facilities that are available for plutonium or mixed oxide fuel. Now that it has been recognized (Mark 1993, Garwin 1997) that it is possible to make an atomic bomb (even if less reliable or low yield) with "reactor grade" plutonium with 25% of the isotope plutonium 240, this emphasizes the importance of secure storage and makes it a problem for many more countries (such as Japan and Germany) than those with excess weapons plutonium. This immediately raises the all important questions:

What, if any, is the difference between the ease of using "reactor grade" plutonium and "weapons grade" plutonium to make an atomic bomb? Can the difference be increased, and can this difference (if any) be translated into a lower cost for protection of reactor grade plutonium?

The heat generation in Pu^{238} (540 Watts/kg) suggests that when there is high burn up fuel with 2% Pu^{238}, there would be enough heat (100 Watts in a 10 kg assembly) to melt any bomb assembly of present design or at least its high explosive trigger. This leads to a set of questions.

It it true that ALL bomb designs in the arsenals of weapons states would fail with 2% Pu^{238}?

Is it true, as one scientist states, "It would not be my preference, of course, but I would have no difficulty in making a highly reliable weapon with 100 Watts of decay heat"?

Would it be helpful to artificially increase Pu^{238} by adding Am^{241} to the fuel rods? ($Am^{241} + n \rightarrow Am^{242} {}_\beta \rightarrow Cu^{242} {}_\alpha \rightarrow Pu^{238}$).

This leads to another question:

How does one define secure storage? what are the criteria?

One used to define it as being sufficiently secure that a terrorist, or agent of a "rogue" country, would find it easier to steal from a military complex. But now there is a real possibility of disarmament, that seems inadequate.

Can one compare usefully possible terrorism with nuclear bombs and terrorism with other material?

It is relatively easy to obtain even large quantities of other explosives. A billion tons a year of ammonium nitrate is used in the U.S., about half as easily available fertilizer. While terrorists used about a ton to try to blow up the World Trade Center and the federal office building in Oklahoma City, it may be worth noting that a string of barges carries 10 kilotons (with the explosive power of a Hiroshima bomb, and a supertanker could carry 300 kilotons (the explosive power of a hydrogen bomb). The accidental explosions at Oppau in Germany and in Texas City, were larger than the Hiroshima explosion, and are examples of what a terrorist might do with ammonium nitrate in the future.

If plutonium is separated from spent fuel the volume is reduced and storage facilities can be smaller. This leads to the question:

Is there an appreciable advantage in storing separated plutonium in a central facility over storing unreprocessed fuel rods in many, dispersed, locations?

5.   PROLIFERATION RESISTANT FUEL CYCLES

It has been claimed, and it seems reasonable, that facilities for chemically purifying small amounts of spent fuel are simple and cheap *if* environmental and occupational safety rules are not

followed - and terrorist groups are unlikely to feel a need to follow them. It is therefore important that all spent fuel be accounted for - presumably by counting of, and measuring fuel rods. While not suggesting that the issue be forgotten, I note that this must be done even for present nuclear power plants, and therefore is not an additional issue for expanding the fuel chain into a fuel cycle. Moreover, over the long term the world must decide what to do about the increasing inventory of plutonium in the spent fuel rods.

It is generally agreed that the most important danger is chemically separated plutonium. Since the most important item for the long term (>50 years) future is breeding fissile fuel from the uranium 238, and not merely using the fissile material in light water reactor spent fuel, I will simplify the discussion below by considering a breeder reactor. This must use fast neutrons, and the usual heat transfer medium discussed is liquid metal (sodium).

The Ford Foundation study raised the scepter of the "plutonium economy", a naive parody of the plans of the time. A world was envisaged with hundreds of breeder reactors, all plutonium fueled, and many in small unstable countries. Chemically pure plutonium, separated from the spent fuel would become an article of commerce and perhaps traded on the commodities exchanges (maybe restricted to the signatories of the non-proliferation treaty). It would then be all to easy for a terrorist to obtain a little plutonium to make a bomb. This image never materialized, and it remains important to describe a viable nuclear fuel cycle which is much safer. Such a cycle might include restriction of the use of a breeder reactor or recycled plutonium, to a relatively small number of industrialized countries with international inspection

A principal task of the designer of a breeder reactor cycle must therefore be to prevent the plutonium being easily diverted to uses as a terrorist or military use. Unless this can be done to public satisfaction, the reactor system is unlikely to achieve public acceptance.

Although a fast neutron reactor does not by itself create a plutonium economy, there seems little point in developing reactors which are probably more expensive if breeding is not to be accomplished. Therefore the fast neutron reactor has become synonymous with the plutonium economy in many minds. It is a useful thought for professionals in the nuclear industry to bear in mind when thinking about the future.

The "ordinary" reprocessing facilities used by COGEMA and British Nuclear Fuels Services (BNFS) follow the PUREX scheme which was designed for the military purpose of producing pure plutonium for bombs. Inevitably there is chemically pure plutonium available in the fuel cycle, although a modification called CIVEX would reduce this. This the raises the all important question:

Are the facilities at COGEMA and BNFS adequately secure?

Can the time available before more reprocessing is needed be used either to modify the existing cycle (e.g. by adding Pu^{238} as suggested above), or to demonstrate more clearly that it is already adequately secure?

6. THE IFR FUEL CYCLE

The success of the group at the Argonne National Laboratory in obtaining a high burn up with metal fuel suggested that a pyroprocessing scheme could be used. The key step in the reprocessing is electrorefining. The disassembled and dissolved fuel elements are first electrorefined to separate bulk uranium on a solid cathode. The remaining uranium along with plutonium and other actinides, minor in quantity but major in proliferation resistance, are electrorefined by deposition onto a liquid cadmium cathode. The cathodes are removed from the refiner cell, the cadmium and occluded salts are removed by retorting, and the uranium and uranium-plutonium actinide product is consolidated by melting.

In this process the minor actinides (neptunium, americium, and curium) and a little uranium accompany the plutonium product stream. Because these elements have similar electro potentials, the process cannot be simply modified to separate them. Moreover the product carries enough radioactive fission products to necessitate remote handling of even refabricated fuel. Unauthorized access is almost impossible and any attempt would be easy to detect. Moreover the process is compact and seems to be favorable in modest sizes. Therefore the fuel facility can be located at the reactor site, reducing the risk (albeit small) of transporting the spent fuel and refabricated fuel.

Technological feasibility of the pyroprocessing and fuel fabrication has been demonstrated and a data base established to ensure its practicality. The EBR-II fuel cycle facility is being refurbished. It is now (summer 1996) processing spent fuel from EBR-II. It had been proposed, and accepted by DOE in previous administrations, to start a prototype demonstration of the entire fuel cycle. However, under rather firm, non technical, instructions from DOE, it is now planned to close EBR-II, and make its restart difficult by removing the sodium. Many technologies proceed without such an integrated demonstration of the complete fuel cycle. But as any engineer knows, a practical demonstration is often worth a thousand good calculations.

This then raises the important question:

Are the potential advantages of the IFR fuel cycle great enough to demand an international effort to demonstrate engineering feasibility of the full cycle?

If the answer to this is yes:

Can the U.S. program be revived, or will the leadership go elsewhere?

7. INTERNATIONAL COOPERATION

The issues that are being discussed at this conference are not the parochial issues of one country, even one as large as the USA or Russia. They are issues that affect the whole world. It is therefore appropriate that the whole world consider them together. The research and development has turned out to be very costly and even the U.S. is reducing its outlays in this direction. It is therefore important to use all available facilities in the world in a cooperative manner.

Fortunately the end of the cold war makes cooperation between Russia and the USA easier. There has been progress. In summer 1994 fast neutron reactor experts from the Argonne National Laboratory were actively discouraged (again by the U.S. Administration) from discussing problems with their counterparts at Obninsk. This has changed. Now Argonne scientists are being informed, for example, of the detail of the fuel loadings at Beloyarsk.

This raises then the following question:

What are the possible ways of using existing internationally available, (or planned) facilities in such a research effort? e.g: Introducing an IFR fuel cycle into Beloyarsk, Monju and/or Phoenix? Modifying Le Hague or Sellafield to become even more proliferation resistant and/or cheaper to operate?

8. ECONOMIC ISSUES

It is clear from the public reaction to terrorist activities on aeroplanes that the public is willing to spend a lot more money to combat terrorist activities than the economists suggest. The economists

suggest a Willingness to Pay of about $4,000,000 per statistical life saved. This puts pressure on nuclear energy to be cost effective in other ways.

Therefore we must ask:

What are the true economic costs of reprocessing using the present PUREX process and can they be brought down?

Studies from OECD suggest that it is now more expensive to fabricate free plutonium fuel than to both buy and fabricate uranium fuel. Any cost advantage for reprocessing would therefore seem to come from a lower cost to dispose of reprocessed waste without transuranics than for ordinary waste. Technical estimates of this cost advantage suggest that it is small. But this is an issue where psychological reasons dominate over technical ones. This leads to another question:

What are the advantages (expressed in $$$) of final disposal of fuel from which the plutonium and transuranics have been removed? including the advantages in public perception?

Until a waste policy exists this has to be a technical calculation only leaving out factors of public perception. This would probably give a very small advantage. But somehow we must figure out what advantages there may be in public perception, or leave this as a variable to be inserted at the last moment.

In this connection it is worth noting that Keeny et al. (Ford Foundation study) argued that spent fuel rods could be placed in a permanent repository almost as easily as the fuel without the recyclable transuranics. While this may be technically correct, in the intervening 20 years there has been no political progress in the U.S. in establishing such a repository.

Other economic questions include:

Is the IFR fuel cycle likely to be as cheap? cheaper? more expensive?

Is it economically preferable to store the excess pure plutonium waiting the 40+ years till a breeder reactor is needed (as the Russians presently plan), or to burn it in MOX fuel in present reactors, and make it again when needed? (bearing in mind the cost of storage)

What would be the economic cost of ensuring that fuel fabrication and utilization facilities have a greater capacity than fuel reprocessing so that plutonium can be burned up as soon as it is separated?

9. OTHER FUEL CYCLES

It seems that everyone who begins to study the future of nuclear power, recognizes very soon the advantages of a thorium fuel cycle *if it can be made to work.* A thorium fuel cycle does not produce plutonium, and although it produces uranium 233 from which one can also make a bomb, the uranium 233 can be quickly diluted with natural uranium for use in light water reactors. However, as soon as it is reused in reactors, plutonium is produced from the natural uranium. Twenty-five years ago, when making a breeder reactor was a national priority in many countries, the projected expansion in the need for nuclear electricity, and a smaller expectation of world uranium reserves, led to a demand for high breeding ratios so that the expansion could be rapid. A breeding ratio less than 1.4 was considered too low. This ruled out the thorium cycle. Since rapid expansion of a breeder reactor program seems not (yet) to be necessary, it is worth asking once again:

Can the thorium cycle be used instead of, or in addition to, the plutonium cycle? Does it possess the advantages that many people claim?

10. ACCELERATOR DRIVEN SUB-CRITICAL ASSEMBLIES

Several authors have begun consideration of sub-critical assemblies driven by spallation neutrons from a particle accelerator (Petrov 1992a, 1992b; Bowman et al., 1992; Carminate et al., 1993) Amplifications by the assembly of 50 are suggested. These ideas are not new, dating back at least to Lewis (1975). At first sight these subcritical assemblies will only solve a problem not considered here - that the public fear of nuclear reactor accidents may be related to criticality. All the fuel cycle problems would seem to be the same. However, the authors propose in addition to using a subcritical assembly to use a thorium cycle. Although not clearly stated, the design turns the safety advantage into a better assembly from the breeding point of view. Thus we should be asking:

Does the extra flexibility obtained by avoiding criticality enable us to use a more proliferation resistant cycle?

11. THE PREVIOUS ACCIDENTS

It has been said that anyone who does not learn from history is condemned to repeat it. Many people still remember the accident in the FERMI-I reactor at Laguna Beach Michigan and the famous (or infamous), but careless, statement "We almost Lost Detroit" (we were far from losing Detroit). The problems with SuperPhoenix at Creys-Malville, where the reactivity dropped suddenly without apparent reason, is a cause of concern. It seems important to be very clear what the reasons for these incidents were, and why they will not occur in any design under consideration. Therefore an important need is to:

Has anyone carefully Recorded, Understood and Explained the past history of breeder reactor technology both of accidents, and of failures and successes? If so, where is it? If not, why not?

12. THE EVILS OF PLUTONIUM

Plutonium is regarded by some of the US public as the embodiment of evil, and the breeder reactor has become a symbol for some public concern about nuclear power. Therefore it is important to understand this concern and how it might be allayed in the future. Plutonium has been called "the most toxic substance known to man" and while this is an untrue statement plutonium is toxic in small amounts. While it can, and should, be kept out of the environment, I note that a ton of plutonium has been evaporated into atmosphere (world wide) from bomb tests and there has been no obvious effect on health. A report written for the ANS study (Clarke et al., 1995) discusses the data in some detail.

Is the Clarke Report on plutonium toxicity widely accepted and if not, why not?

Some MAYAK workers had over 1 μCurie of plutonium in their skeletons - over 10,000 the normal amount. Although adverse effects on health were seen, they were comparable to cigarette smoking.

Can the MAYAK experience be used to help in public understanding?

13. NUCLEAR PROLIFERATION

It is likely that public perception will still depend on our ability to control nuclear weapons proliferation among countries. Those that espouse nuclear power and in particular a breeder reactor program which closes the fuel cycle cannot afford to ignore this issue. This is of course a major concern of IAEA and is discussed elsewhere.

On the first count I suggest that it is instructive to understand the reasons why a country decided to make nuclear weapons. Even more important why a country decided NOT to and whether we can reinforce these reasons. A major reason why a country decided to make them was prestige. England and France did so to be taken seriously by the USA. In this the USA was at fault, and continued to be at fault for some time, in only taking seriously these countries after they had a bomb. South Africa has dismantled its few weapons, not wanting them to be controlled by the ANC. Brazil and Argentine, stimulated I am glad to say by the Physical Societies of both countries, realized that a bomb program no longer gave prestige and have abandoned their programs. It is vital for scientists to go out and talk to the potential proliferators, understand their concerns and try to address them. Alas few US scientists and diplomats do this, but instead lecture to them from Washington or academia. Iyengar (1995) noted that "as long as nuclear non-proliferation initiatives restrict their attention to the spread of nuclear materials and 'know-how' from the 'haves' to the 'have nots', without taking into account the needs, fears and capabilities of the non-nuclear states they are doomed to failure." We must consider the developing countries. I do not think the rest of the world will persuade India away from its position that NPT is a discriminatory (colonialist) treaty.

Can more imaginative, quiet, talks with India and Pakistani leaders persuade them to come to a non-nuclear agreement on their own which would satisfy the rest of the world?

I would like to see answers to these questions in various (coupled) ways. A detailed technical paper on each one; a technical survey (with reference to the detailed papers) suitable for a weekend read by any physical scientist, and a mere elementary summary for high school students. All on the World Wide Web with links to everyones' papers. Nothing less will do.

I end this part of the paper with a plea similar to that made by Andrei Dmitreyvich Sakharov to the German "Greens" at the "Congress on a Nuclear Free World" in Moscow in 1987. Rather than spend all their energies opposing nuclear electric power, Andrei challenged them to spend their energies making it safer and more secure. That seems to me to be the challenge for a forward looking scientist or politician.

14. WHAT CAN WE DO?

There are few people actively pushing nuclear energy right now. In the early 1980s, a group from the Kennedy School of Government pointed out the "Director's Dilemma" explaining why no electricity company director would propose a nuclear power plant under the conditions of the time (which have got worse). Only a few lonely academics seemed to be in favor. Many of us deserted the Democratic party in the 1988 presidential election because we could not abide Michael Dukakis' anti-nuclear actions.

Now even the academics have lost hope. I have not heard the subject even mentioned in the recent elections. I cannot get anyone in the MIT Nuclear Engineering Department concerned about the fate of Northeast Utilities. It may only be the older dreamers like those of us here who have any interest left. I suggest a number of possible steps:

Suing the NRC to make them abide by their own guidelines (a public interest law foundation might help).

Asking each and every candidate for any political office his views on the subject and making the issue a deciding one in any and all elections.

Trying to ensure that our disease is not caught by other countries. This one might do by actively explaining the situation to other countries, such as France, Japan and Russia. In this connection the

letter, just made public, by Professor Glenn Seaborg to the former French President, Valery Gisgard D'Estaing is of great importance.

Maybe meetings such as this might have a press conference and present a resolution on the subject.

I was educated in Oxford University, known as the home of lost causes. May be this is just another lost cause.

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CLOSING SESSION

SUMMARY OF THE SYMPOSIUM

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1. INTRODUCTION

The reason for organizing this symposium was to face the new realities in the nuclear fuel cycle and to come to conclusions on how they should be addressed. The "new realities" are:

- an unexpectedly slow growth in nuclear energy
- the escalation of back end costs
- the delay in the introduction of fast reactors, and
- the end of the Cold War.

The consequences of these changes are:

- a surplus of uranium
- a continued debate over the choice of the fuel cycle
- a surplus of separated plutonium
- the demilitarization of weapon plutonium and high enriched uranium.

The Working Groups included participants from 12 countries and 4 international organizations. Since the scope of this symposium is wide — technical, political, legal — the participants had very different backgrounds: physicists, chemists, engineers of all kinds and political scientists. This made the discussion very interesting and lively.

As a basis for the work of the different Working Groups it was necessary to establish some kind of outlook into the future of nuclear energy for the next 50 years and this was the task of Working Group 1.

2. GLOBAL ENERGY OUTLOOK

Key Issue Paper 1 and a paper from Los Alamos [1] discussed world scenarios from different viewpoints. Two other papers supplemented the theme by considering regional or even national aspects. Before entering the discussion on scenarios for the future let us summarize — on the basis of Key Issue Paper 1 — the situation as it is today:

Worldwide there are 437 nuclear power plants with a capacity of 345 GW(e) in operation, producing 2200 TW·h (in 1995) which corresponds to about 17% of the world electricity production. Thirty-nine nuclear power plants with a capacity of 32.6 GW(e) are under construction. This represents a remarkable achievement if one considers how young nuclear energy is and the obstacles it had and has to overcome.

The three nuclear energy scenarios considered by Key Issue Paper 1 are as follows:

By 2050	high variant	1805 GW(e)
	medium variant	1132 GW(e)
	low variant	333 GW(e)

The bases for these scenarios were explained in detail during the symposium. The scenarios were based on studies by IIASA and the WEC and were characterized as "contrasting but not extreme". No disaggregation into regional scenarios was made.

In contrast to the Key Issue Paper, the paper by Los Alamos [1] established new energy scenarios by the "use of 'scenario building' techniques, where a spectrum of possible futures is quantified by means of a series of well defined, simplified and generally surprise-free assumptions." A global energy,

economics and environmental model [E³] was adopted, leading to consistent scenarios in which future demands for nuclear power are projected in price competition with other energy sources under a wide range of long term demographic, economic, policy and technological drivers. The scenarios cover the time span up to 2100.

These scenarios are new and independent and therefore different from the IIASA and WEC studies, but the Los Alamos curves for total primary energy and nuclear energy up to the year 2050 are not that different from the medium variant of the Key Issue Paper. In all cases, we are not dealing with predictions here but with scenarios. For our purpose — the possible requirements for the fuel cycle — it is enough to know that the truth is likely to lie between the high and the low variants.

What are the consequences for the fuel cycle? The Key Issue Paper clearly shows that the uranium resources suffice to cover the requirements for the low and the medium variant. In case of the medium variant, however, there may not be sufficient uranium resources to cover the years after 2050 for reactors existing in 2050 if one assumes that these reactors will continue to operate up to 40, perhaps even 60 years after their startup. Therefore, ways and means to make better use of the resources and their potential influence are of importance.

Fuel utilization in thermal reactors can be improved in three ways:

– lower the tails assay in the depleted stream of enrichment plants
– go to higher burnup fuel
– recycle plutonium.

By reduction of the tails assay from 0.3% to 0.15% almost 25% of uranium can be saved as compared to a saving of about 17% by recycling all plutonium in LWRs. The cumulative impact is shown in Key Issue Paper 1. Whether all these possibilities will be used, will, of course, primarily be an economic and political question. These points will be discussed later.

As a consequence, the Key Issue Paper assumes the introduction of the fast reactor after 2030; by 2050 fast reactors are projected as having a share of about 10% of the nuclear capacity. They are assumed to be introduced slowly, as a result of problems of economics, acceptance and availability of plutonium.

The Los Alamos projections introduce fast reactors, even under their most favourable scenario, much later. Ten per cent will, in the best case, be reached only around 2100. It is important to note that, according to the Los Alamos model, the greatest impact in favour of nuclear energy is produced by a possible carbon tax.

Both papers look at the world as a whole — without barriers for trade; even plutonium is assumed as being traded on a world market.

The two remaining papers on the situation in East Asia and the Russian Federation take a more regional view. The Japanese paper [2] projects that East Asia will dominate as far as the increase of nuclear energy is concerned. We will see the same data again in Session VI. The reasons are manifold: relatively small per capita energy consumption in the region today, high population growth rates, high GDP growth rates, especially outside the Far Eastern OECD countries, lack of fossil fuels except coal and limited possibilities for renewables. If East Asia covers its energy requirements primarily by coal, the paper states that the world will face a very serious CO_2 problem and that nuclear energy in this region is therefore of the highest importance.

After discussing regional aspects we had a look at one single country. Paper [3] dealing with the power strategy in the Russian Federation refers to the Russian situation only. This situation is very specific: although the Russian Federation has very large coal and gas reserves the existing infrastructure makes it difficult to transport the fuel to certain locations in an economical way. This, the paper states, makes nuclear power competitive in these areas. However, Russia does not have major uranium deposits (although it does have stockpiles sufficient to cover the needs up to 2010) and as a consequence it is the

294

country that looks at fast reactors with the highest degree of optimism. This is partly justified by the good experience with the BN 300 and BN 600 reactors, which have been operated for a long time, albeit with high enriched uranium (HEU) and not with plutonium. The transition to plutonium is in the demonstration phase.

3. PRESENT STATUS AND IMMEDIATE PROSPECTS OF PLUTONIUM MANAGEMENT

Session II dealt with the present status and immediate prospects of plutonium management up to the year 2015 — giving special consideration to the problems of plutonium management. If we look back to the INFCE (International Fuel Cycle Evaluation) times, some 20 years ago, not very much seems to have changed as far as policy is concerned. INFCE was triggered by the US conclusion that a once-through fuel cycle with no separation of plutonium had the least proliferation risk and the lowest cost. Several other countries decided at the time of INFCE that the best approach to the fuel cycle was to pursue programmes to reprocess spent fuel to remove plutonium and recycle it to recover its energy value, while relying on safeguards to prevent proliferation. Most of these countries have not changed their positions since. In the meantime a large and viable recycling industry has been established in France and the UK or is being established as in Japan and the Russian Federation . This involves reprocessing plants, facilities for the manufacture of MOX fuel elements and reactors licensed to use MOX fuel. Some countries, like Germany, have forgone establishing their own recycling facilities but use MOX fuel produced in other countries. Finally, it has become evident in these past decades that fast reactors will be delayed and their commercial introduction is not expected before the year 2030.

Both the Key Issue Paper 2 and the NEA paper [4] deal with the experience accumulated in MOX fabrication — for both thermal reactors and fast reactors. In summary, 630 t of MOX fuel have been fabricated and irradiated in reactors; currently 21 thermal reactors in five countries are loaded with MOX fuel and this number is expected to rise to between 36 and 48 by 2000. The existing MOX fuel fabrication capacity is more than 200 t/a and will quickly rise to about 400 t/a. Therefore, recycling is now an established technology. However, it should be pointed out that in all three scenarios of Key Issue Paper 1 4000–5000 t of MOX fuel fabrication capacity will be needed by 2010 if all spent fuel is to be recycled.

The controversy over whether recycling creates higher proliferation risks and is more costly than the once-through cycle remains. Several studies have been performed, and they have been mentioned during this symposium. A study performed under NEA auspices and reported here [4] came to the conclusion that the cost differences between the reprocessing option and the direct disposal option are small (direct disposal being about 10% cheaper in power generation costs) and, considering the uncertainties, this small difference in the fuel cycle costs was considered to be insignificant. A recent study by the US Academy of Sciences, however, concluded that there was no reason to change the current once-through approach because recycling would bring no benefits and would increase the proliferation risk.

The delay of recycle in either thermal or fast reactors has led to a buildup of separated plutonium inventories that is viewed by many as requiring reduction — another of the new realities. The Key Issue Paper 2 gives detailed figures on total generated and separated plutonium and discusses the question whether and how this plutonium inventory can be reduced. It may be worthwhile repeating some of the figures for the end of 1995 here:

— about 970 t of Pu have been generated in 180 000 t of spent fuel
— about 185 t of Pu have been separated
— and about 50 t of this have been recycled.

This means that about 135 t of plutonium were in store. By the end of 1999 the estimated worldwide inventory of separated Pu will reach about 175 t. Through the introduction of MOX fuel this inventory will decrease after 1999 and level out at about 135 – 140 t. This model calculation assumes that each country is recycling only the plutonium that was produced in its own reactors. Since there are countries that separate plutonium from their own reactors without recycling (UK — with no plans to recycle, and the Russian Federation — with intentions to recycle) the inventory will eventually rise again. This rise in inventories could be averted only either by using the plutonium in these countries or by transferring the

plutonium to countries that would use it. In this case, the inventory could be reduced to less than 50 t and would remain at that level which is necessary as the working stocks for the MOX and fast reactor fuel manufacturing plants. However, even if all political obstacles to such a plutonium transfer could be overcome, in the time frame up to 2015, the economics of recycling would still affect the viability of this approach.

A very interesting subject discussed in Session II was the disposition of weapons plutonium. This was not only part of Key Issue Paper 2 but was also the subject of two papers presented orally and several poster session papers. The fact that the two major nuclear weapons states — as a result of the end of the Cold War — are willing to reduce their nuclear arsenal is an important new reality. This, of course, applies not only to plutonium but to HEU as well. The programme to blend down HEU of Russian origin to LEU for use in reactors has aptly been called the "megatons to megawatts program". Other very positive aspects of the disposition of weapons material are that it constitutes a truly international endeavour and that the material will be subject to international safeguards and verification at an early stage. We will come back to this issue in Session VI.

The programme described in the Harvard Center Paper [5] was the subject of summit meetings between the Russian Federation and the USA and the programme was also discussed by the P-8 Group in Paris in October 1996. However, it will have to overcome many hurdles before it can be implemented. The USA has declared 50 t of plutonium as excess to military needs; Russia has declared that it will also transfer fissile material out of its military programme but has not yet declared the quantities to be transferred. It is widely agreed that the disposition programme should be accomplished as quickly as possible, but so far the necessary funds have not been identified and committed.

The USA has adopted a "dual track approach" for disposition of former military plutonium, meaning that using the plutonium in MOX fuel and disposing of it as vitrified waste should be utilized. However, the use of excess plutonium as fuel in reactors has been criticized in the USA as inconsistent with the US policy of not supporting reprocessing and recycling of plutonium. The Harvard paper stated: "The principal obstacle to implementing plutonium disposition in the United States is politics; the principal obstacle in Russia is money". In discussing the problem of plutonium disposition it is necessary to keep the magnitude of the problem in mind: the USA has declared 50 t plutonium as surplus; if it is assumed that the Russian Federation will dispose of a similar quantity, the total will be about 100 t. In comparison, about 50 t of plutonium have already been recycled and by 1999 civil stockpiles will reach about 175 t. Adding to this the ex-military material does not change the order of magnitude of the problem. If the civil material can be handled, then the ex-military material can be handled as well. What is needed is the political will to address and to solve the problem, the necessary funds and effective international co-operation.

If the need arises to dispose of large quantities of plutonium (of military or civil origin), fast reactors could be used as plutonium burners.

4. FUTURE FUEL CYCLE AND REACTOR STRATEGIES

Session III dealt with the time period from 2015 to 2050. What kind of developments in reactors and fuel cycle technologies are we going to see during this period? Will we be faced with entirely new technologies or will we rather have to rely on the continuous development of the existing concepts? How can we deal with different scenarios of nuclear capacities as they were discussed in Session I?

In dealing with these questions, Key Issue Paper 3 first introduced a set of factors influencing future reactor and fuel cycle concepts, then it discussed the different reactor systems, to end in defining trends in the nuclear fuel cycle. The orally presented papers have supplemented Key Issue Paper 3.

It goes without saying that looking at the time period from 2015 to 2050 is more speculative than discussing the immediate future. Nevertheless, there was general agreement that the next 50 years will be dominated by thermal nuclear reactors and that these reactors will continue to play a significant role beyond the year 2050. So, by 2050, we will very likely see a mixture comprising a large population of thermal

reactors with a small population of fast reactors which is forecast to grow steadily in the years after 2050. This corresponds well with the conclusions drawn in Session I. However, as paper [6] by an international group stated, "it may become essential to 'branch out' from familiar designs in order to maintain competitiveness with other energy supply options".

In general, we will have a large number of new thermal reactors characterized by the letter "A" for "advanced", e.g. ABWR and APWR. Other advanced thermal reactors do not use the letter A, e.g. the EPR or the advanced CANDU. For the major part of the reactor population we can expect an evolution and not a revolution.

More revolutionary reactor concepts continue to be proposed, including the Radkowski Thorium Fuel Reactor (RTF), modular HTGR and combinations of nuclear power plants with gas turbines. The concepts will require significant further development before possible commercialization. During the discussion the inertia of nuclear technology was mentioned. This will make it difficult for new concepts to succeed.

Let us concentrate on the direction this evolution may take. Key Issue Paper 3 defines seven "factors influencing future reactor and fuel cycle concepts" and other papers follow this list, although sometimes in different order and with different words. We have heard them several times: natural resource utilization, economics, environmental impact, safety, public acceptance, national and international policies and sustainable energy supply.

What does this mean for the LWR fuel cycle? Paper [7] (BNFL with international contributions) introduced the concept of the "holistic" fuel cycle considering the complete fuel cycle as a whole rather than as a number of individual stages. This concept integrates the various options for fuel manufacture, reactors, reprocessing, waste management and decommissioning to optimize the whole fuel cycle.

What fuel cycle technologies can be expected in these next 50 years? As has been mentioned before, enrichment may have a tendency to go to lower tails assays. The diffusion plants will all be closed down in the time period we are considering and will be replaced by centrifuge and/or laser plants. Centrifuge plants are built in small increments which enable the operators to bring in new, improved design continuously. The centrifuge technology is therefore a moving target. If, however, because of high uranium prices optimum tails assays will become very low or recycled uranium becomes important as a fuel the laser enrichment methods that can separate isotopes very selectively will have advantages. This is, of course, not to say that AVLIS, SILVA or MLIS may not be introduced in any case because of economic advantages.

The long term evolution of fuel product and manufacturing technologies will largely be dictated by the mix of reactors that exist. Key Issue Paper 3 gave an expiration schedule for existing world nuclear power plants. The number will start decreasing significantly after 2010; by about 2035 all existing reactors will have been shut down. The key question for the future of our industry is whether these reactors will be replaced by nuclear plants or by fossil plants.

Let us go back to the fuel technology. A level of 55–60 GW·d/t is viewed as the limit for technical and economic reasons for recycle fuel; only fuel for the once-through cycle may be driven to burnups in the order of 80–100 GW·d/t. However, new claddings will be required. If other thermal reactor concepts like the HTGR are introduced, different fuel elements that have already been developed in the past — such as fuel using coated particles — will have to be produced. This fuel could achieve very high burnups, well beyond 100 GW·d/t, and would also be very useful for burning plutonium. Advanced fuel concepts may be introduced gradually between 2015 and 2050.

In the case of the recycling of plutonium in thermal reactors there are limits to the number of recycles possible. Multiple recycling produces degraded plutonium which limits the number of recycles in thermal reactors to two to three. Such degraded plutonium can, however, be used as a fuel in fast reactors. If such reactors or other effective plutonium burners do not materialize, spent fuel, although in reduced quantities, will still end up in final repositories.

Paper [7] postulated an evolution in which advanced or new reprocessing technologies will be commercialized in the time period we are looking at (2015–2050). Aqueous reprocessing — PUREX, 50 years old — will remain as the base technology but will be constantly improved to achieve lower activity levels, less waste and cost reductions. Several programmes have been undertaken which are not only innovative and technically impressive but which also confront us with many new acronyms like: SPIN, PURETEX, ACTINEX, DIAMEX and SESAME. This shows that the nuclear community is innovative in finding new words, too. New flow sheets based on non-aqueous reprocessing methods will be introduced after 2015. These processes tend to be shorter and simpler and also offer safety advantages. The methods considered are molten salt, fluoride volatility and, although it does not involve reprocessing, DUPIC. The general trend, be it with conventional or with new technologies, is towards reduced costs and improved safety.

MOX technologies exist as has been shown before. The costs for producing MOX fuel should become lower. Today, MOX fabrication costs are 4–5 times higher than for conventional UOX fuels; increased MOX utilization should lead to manufacturing costs of less than three times that of uranium fuel. Thus both reprocessing and MOX fuel fabrication will become cheaper.

Industrial fabrication of fast reactor MOX fuel is likely to be based on the proven MOX technology for LWRs. New developments may be closely linked to the advanced PUREX and pyrochemical reprocessing which aim for coextraction of plutonium and uranium with low decontamination factors. This will require new fabrication technologies which may lead to the integration of fuel fabrication, reprocessing and waste treatment in one plant.

Several papers, also in the poster session, dealt with partitioning and transmutation (P&T). The aim is to separate the actinides and long lived fission products and then reduce their toxicity by transmutation. This should reduce the long term hazard of reprocessing wastes. Again, here we have different views in different countries: those that follow the recycle route (e.g., France, Japan and the Russian Federation) and expect to introduce fast reactors in the future believe P&T to be of importance, other countries, such as the the USA, have studied the problem and come to the conclusion that it would not produce major benefits [8].

Of great importance is of course the waste and disposal problem. This concerns not only the waste from the power plants operating in the past and presently but also the huge amounts of "historic wastes" that are in store from the weapons programmes. The general opinion was that disposal, be it direct disposal of spent fuel or disposal of vitrified waste coming from reprocessing plants, is primarily a political and not a technical problem. Several speakers also did not consider it as very urgent, because spent fuel and glass blocks can be stored for extended periods. However, there seems to be general agreement that for reasons of public acceptance at least one repository has to be brought into operation as soon as possible.

Fast reactors are expected to be introduced gradually between 2030 and 2050. Key Issue Paper 3 gave a figure forecasting that by 2040 only between 10 and 15 GW(e) will have become operational. Some participants consider this scenario as too optimistic. Paper [9], authored by representatives of the three countries that still have a major fast reactor programme (the Russian Federation, France and Japan) dealt in detail with the R&D targets and the outlook for fast reactors. This paper also comes to the conclusion that fast reactors will not be needed before 2030–2050 and that the major improvements are necessary in economics and safety.

Some emphasis in oral and poster papers has been put on systems based on thorium fuel, thorium representing a vast resource for nuclear energy. Although thorium fuels have been used in several countries, it was the general opinion that a widespread use in the next 50 years is going to happen only in a few countries such as India. The reason for that is that there is a complete infrastructure for uranium fuel in existence and it is unlikely that a complete new infrastructure for thorium will be built up on a worldwide basis. If thorium is used, it is probable that the fuel would contain thorium boosted by either uranium or plutonium, in a once-through mode.

5. SAFETY, HEALTH AND ENVIRONMENTAL IMPLICATIONS OF THE DIFFERENT FUEL CYCLES

In dealing with future fuel cycle strategies, it is important to evaluate whether significant differences can be identified among the three fuel cycles in terms of occupational and public exposure and other environmental impacts. Key Issue Paper 4 and four orally presented papers dealt with these issues. In addition, we had several poster papers concerning health, safety and the environment. It was stressed that the nuclear fuel cycle is probably the industrial system which has been the most scrutinized as far as risks to human beings and the environment are concerned. It is certainly also worth mentioning that the risks and impacts of the fuel cycle are small compared to those of nuclear power plants and that within the fuel cycle mining is the major contributor to occupational and collective doses.

In this context is was very interesting to hear [10] about the progress that has been made throughout the mining industry in controlling exposures, both occupational and collective. New mining methods like non-entry mining, grouting and freezing, combined with continuous radiation monitoring equipment in mines and mills, have all helped to reduce radiation exposures in mining and milling. The same holds true for the management of tailings, where new methods have been developed and applied so that today uranium tailings and other uranium mining wastes are well managed. This was not always true in the past and therefore remedial action programmes have been implemented or are being planned for tailing sites that were not properly treated in the past. Examples of this are the USA (26 old sites), Germany (former WISMUT site) and a number of central and eastern European countries that are being remediated with technical assistance from the IAEA.

As one of the pivotal principles in all nuclear installations the importance of maintaining a "safety culture" was identified. "Safety culture is that set of characteristics and attitudes in organizations and individuals which insures that, as an overriding priority, nuclear plant safety issues receive the attention warranted by their significance". In this context the importance of international organizations like WANO, NEA and the IAEA that enhance international co-operation in order to improve safety was stressed.

There are, however, still some elements of the environmental safety issue that remain controversial. As an example, there are opposite views on the risk associated with low level radiation exposure. (The dispute is whether the biological effects of radiation remain linear down to zero exposure or whether there is a threshold below which these effects disappear.) Another example is the problem of very long term potential impacts of radioactive wastes and long lived radionuclides released into the environment and affecting large populations. Of course, methodological, political and moral dimensions involved in these questions could not be resolved in the framework of this symposium.

In the nuclear fuel cycle industry, as in the nuclear energy industry in general, emphasis has been put on keeping all exposures as low as reasonably achievable — the "ALARA principle". As a result of the applications of the principle consistently, the exposures to both workers and the public over the last decades have been reduced substantially. Quantitative examples for this reduction are given in Key Issue Paper 4 and [10]. As an example it should be mentioned that the average doses and the total collective dose in Sellafield have all decreased by almost an order of magnitude over the past 15 years; similar results were reported for La Hague.

There is only limited experience available worldwide in the management of waste and most advancements remain still at the research and development level. A big step forward in coming to a common approach at the international level will be the "Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management" that exists as a draft and hopefully will come into force in the foreseeable future. Nevertheless, the attempt to evaluate the impacts on health and safety over very long time periods (100 000 years and more) remains challenging because it raises theoretical issues related to the validity of the quantitative assessment of future risks and the ethical position towards future generations. More work, related not only to nuclear energy, but also to fossil fuels remains to be done in order to find a good indicator.

In normal operation there are no significant differences among the three fuel cycles. Long term storage and disposal of spent fuel elements and radioactive wastes do not raise any particular problems in terms of health. Since this symposium has focused somewhat on plutonium, it is interesting to note — as clearly stated in Key Issue Paper 4 — that plutonium toxicity is nowhere a major factor in the context of normal operational impacts. Common to all three fuel cycles is, however, the fact that major accidents may have significant health and environmental consequences. The prevention of such accidents is of the highest importance and improvement of safety is an ongoing task. It remains to be noted that nuclear energy was the first industry to explicitly explore all the potential health and environmental impacts and try to assess and control them. The most recent studies show that the impacts of the nuclear fuel cycle are of the same order as those of energy production by gas or renewables such as wind and hydro. They remain far below the impacts of coal and oil.

Separation and transmutation of radioactive waste is controversial. Paper [8] (MIT and Berkeley) came to the conclusion that such a system "would not bring sufficient merit for the US to delay the development of the first nuclear waste repository for commercial spent fuel". A next symposium in several years may come to a consistent view; by then the major ongoing research programmes in France, the Russian Federation and Japan may have produced reliable results.

6. NON-PROLIFERATION AND SAFEGUARDS ASPECTS

In trying to cover the fuel cycle with its different aspects comprehensively, one has to deal with non-proliferation problems. In fact, the external fuel cycle is more sensitive to these problems than the operation of reactors. Key Issue Paper 5 gives a very comprehensive view on the historical development of safeguards measures and also gives a detailed compilation of all the treaties and agreements that form the existing non-proliferation regime. The paper then goes on to describe new initiatives; it shows that the global non-proliferation regime has continuously evolved in accordance with the international political situation and the development of nuclear energy technology. Since developments of this kind will never stop, the non-proliferation regime needs continuous adaptation to "new realities". There are two recent developments which are good examples of this.

The first example is the strengthening and streamlining of IAEA safeguards, the so-called Programme 93+2. It was triggered by the discoveries of undeclared nuclear material and facilities in Iraq and by the difficulty of verifying the nuclear inventory in the Democratic People's Republic of Korea (DPRK). This highlighted the need to update the safeguards system and give the IAEA an improved capability to provide assurance regarding the absence of undeclared material and activities. Programme 93 +2 provides the IAEA broader access to information from States and increased physical access for inspectors in States. On the efficiency side, it foresees optimal use of the present safeguards system by employing advanced technologies and increasing co-operation with national and regional systems. Part 1 is in force. Part 2 was approved by the IAEA's Board of Governors at a special meeting on 15 May 1997. It will be implemented as quickly as agreements can be concluded with Member States.

The other example is the verification of fissile materials declared excess to defence needs and removed from weapons programmes. The declaration of the Moscow Nuclear Safety and Security Summit contains a number of references to excess materials and related verification issues. The declaration also states that the material will be safely stored and protected and will be placed under IAEA safeguards. Since 1994 the USA has already voluntarily put 12 t of ex-military fissile material under IAEA safeguards. As a follow-up, a trilateral initiative between the Russian Federation , the USA and the IAEA was announced in September 1996 to consider practical measures to achieve this.

If we look at the orally presented papers we find other examples of how necessary it is to continuously develop safeguards and transparency measures. The British/French/Japanese Paper [11] points out that the arrival of large throughput, highly automated plutonium handling plants (such as the Thorp, UP2-800, UP3 reprocessing plants and the MELOX, SMP and PFPF MOX fuel fabrication plants) heralded an era of evolution in their safeguards approaches. The old mass balance "black box" concept has been replaced by a "transparency" concept which needed new and novel techniques. The safeguards approach becomes more plant specific in nature, more pervasive in depth and more cognizant of the

technical evolution. This paper, as well as others, points out that it is very important to agree at an early stage on the safeguards approach and to take it into account during the design and construction phases of a plant. This will be equally true for novel techniques like laser enrichment or dry reprocessing methods.

The Swedish/German paper [12] shows that conditioning plants pose no new problems to safeguards. However, geological repositories call for a new approach. In the case of final repositories for spent fuel a major quantity of plutonium will be underground and this calls for continuing safeguards control. The safeguards strategy for a closed repository is currently under discussion and development. The so-called SAGOR group is working on proposals for specific safeguards techniques which will be presented soon.

Non-proliferation and safeguards aspects of alternative fuel cycle concepts were dealt with in paper [13] (Argonne). This discusses the DUPIC cycle, the fast reactor single-cycle co-extraction concept, thorium–uranium fuel cycles and excess plutonium disposition cycles. It comes to the conclusion that the different fuel cycles can differ significantly concerning the required level of technical safeguards measures. For all the cycles mentioned a list of necessary measures to allow safeguarding are given. Again, the paper stresses that at a very early stage of the development of new processes the safeguards approach has to be defined and agreed upon and that the necessary R&D work has to be performed.

Paper [14] (Argentina, Brazil) gave an interesting overview on the ABACC regional safeguards system which includes a quadripartite agreement between Argentina, Brazil, the ABACC and the IAEA. The bilateral safeguards principle is that inspectors of one State (Brazil or Argentina) control the work in the other State. In this respect it differs from the Euratom system, which involves an independent regional safeguards inspectorate to control 15 States. Whether the ABACC model can be applied in other regions of the world remains an open question.

The safeguards and non-proliferation system has evolved over more than 30 years. This month it has reached an important juncture, with the full approval of the new measures developed in Programme 93+2. This is, however, an evolutionary and not a revolutionary step. In the future not only will new technologies in the fuel cycle be commercialized (as we have heard in Session III), but also the quantity of fuel will increase and more countries will embark on activities in the fuel cycle. The safeguards system and the export control system will both have to keep pace with these developments. However, it is expected that new processes will be safeguardable as earlier processes have been.

7. INTERNATIONAL CO-OPERATION

The final session dealt with International Co-operation. We have a very comprehensive Key Issue Paper and we had six papers presented orally — more than in any other session. This is no surprise — the peaceful use of nuclear energy was probably the only major economic undertaking that from the very beginning was based on international co-operation. Key Issue Paper 6 discusses the history of international co-operation and the situation today in detail.

Paper [15] gave an introduction to the "Guidelines for the Responsible Management of Plutonium". It describes the results of an intergovernmental attempt to formulate agreed guidelines for the management of non-military plutonium. The work is the result of an informal group of nine States engaged in the use or the production of separated plutonium. The aim of the group was to produce a set of guidelines which hopefully will be generally accepted. Acceptance by governments of the guidelines would lead to increased transparency and may thus positively influence public confidence in this area of nuclear operations.

The next paper dealt with the USA–Russia co-operation in the disposition of weapons grade material [16]. It was interesting to hear about the tremendous amount of work that has been done under this joint programme and about the organizational structure that has been built up by the two countries to supervise the programme. The programme assumes that 50 t of excess plutonium in each of the two countries will be disposed of, but also extrapolates the results to larger quantities up to 100 t each. There is agreement between the USA and the Russian Federation to convert the ex-weapons plutonium to the "spent fuel standard" in order to ensure non-proliferation control which means either introducing the plutonium into

MOX fuel elements and irradiating them in reactors or immobilizing it in glass or ceramics. As mentioned before, the USA has opted to follow a dual track strategy — i.e. plan for both solutions; the Russian Federation plans to use the material in thermal and fast reactors and is even considering including future reactors like the HTGR and a future BN 800 for disposition. The WWER-1000 reactors in the Russian Federation and the Ukraine can be used for MOX fuel. The USA and the Russian Federation need not use the same disposition technology but the programme should be done in parallel and must be irreversible. The paper notes in connection with security and accounting that bilateral monitoring might be applied earlier than IAEA safeguards.

This symposium has in its title "New Realities". The demilitarization of weapons plutonium is one of the most important new realities and it is heartening to learn that not only the two major nuclear weapon States are involved in it but also other countries. The Canadian CANDU reactors are being studied as an economic alternative to burn MOX fuel, the AIDA/MOX programme is a Russian/French programme with German participation and the joint Russian/French/German project of a MOX pilot plant for 1.3 t of weapons plutonium per year are examples for the involvement of other countries. The difficult task of ex-weapons plutonium disposition can be carried out only as a truly international undertaking. Even so, the paper concludes, the disposition of 50 t of Pu could only be accomplished "within 20–40 years from when the programme begins". The paper ends with the statement that technical work, political work and financial work remains to be done, the latter two being the primary obstacle to accomplishing plutonium disposition.

Paper [17] dealt with the development of nuclear energy and regional co-operation in Asia. Within a relatively short time period this paper forecasts 100 nuclear power plants in operation in this region due to a rapid expansion of the energy demand and the shortage of other energy resources, East Asia will become a nuclear market of similar size as the USA and Europe with the difference that East Asia will be a growing market whereas Europe and the USA are stagnant or even declining markets. There are, however, not the necessary institutional arrangements in place for a close multinational nuclear co-operation embracing the entire region. The most urgent issues such as ensuring safety, attaining public acceptance, intermediate storage of spent fuel and disposal of radioactive waste call in the long term, in the author's view, for a system of joint research and development and a regional safeguards system similar to Euratom. Models for an ASIATOM (regional) and PACIATOM (regional plus USA and Canada, etc.) have been suggested but are not expected to be realized before 2020, if ever.

The paper on international co-operation with regard to regional repositories for radioactive waste disposal [18] describes an effort by a group of experts from South Africa, Australia, Germany, China and Switzerland to define the conditions to be met and a possible organizational and institutional structure for an international repository. This proposal follows similar lines as the International Monitored Retrievable Surface Store (IMRSS) mentioned in Key Issue Paper 5. The paper lists the benefits of such an international storage and the typical profiles of host and offering countries. However, it does not suggest any specific country to perform such functions.

Finally we had paper [19] on "Closing the Fuel Cycle — Reaching a Public Consensus" under the auspices of the Sakharov Institute. We have purposely put this paper at the end of the Working Session because it in itself summarizes very precisely the obstacles nuclear energy is faced with. This paper states that only nuclear energy is sustainable for a long time at known modest cost. Sustainability does, of course, call for the introduction of fast breeders sooner or later and therefore demands a continued research and development effort in this field. Key Issue Paper 6 comes to the same conclusion. From a non-proliferation point of view the paper by the Sakharov Institute discusses breeder reactor cycles that prevent easy diversion of plutonium. In this context the IFR (Integral Fast Reactor) is discussed and the importance of an international effort to develop this concept is called for.

Key Issue Paper 6 concludes that the arrangements for co-operation in peaceful uses are generally adequate but that there are areas where improvements are desirable.

In conclusion, some points that characterized the discussions in the Working Groups should be noted:

– In the past 25 years development of nuclear energy, at least in the industrialized countries, has been obstructed mainly by the lack of public acceptance, which was also reflected in political actions against nuclear energy or certain nuclear development lines.

– Being far from having achieved public acceptance, the nuclear community is faced with a new difficulty: in some countries nuclear energy has lost its competitive edge. Regaining competitiveness will be the main target for the near future.

– There is a strongly held view that in the long term the world cannot be supplied with clean energy without nuclear power. In the interim, however, we may witness the diminishing of the reactor population. Only in about 20 years will we know for sure how serious the threat of global warming is. Nuclear industry cannot be switched "on" and "off". Therefore we will have to retain the facilities, resources, training and competence [7]. This has to be done within an international network.

– A similar issue discussed in the Steering Group postulates a scenario calling for a rapid take-off of nuclear energy some time in the next century from a low starting point — after an extended period of stagnation. The conclusion was drawn that for that scenario the technical and institutional arrangements would have to be in place. Therefore it would be appropriate to prepare for these arrangements now in order to avoid a crisis once the need for rapid deployment of nuclear power plants comes up.

In summary we can say that the symposium gave a comprehensive overview on the situation of the nuclear fuel cycle today and in the near future, and it presented an outlook on the developments expected up to the year 2050.

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