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Volume 2 of 9

Nuclear Proliferation and Civilian Nuclear Power

Report of the Nonproliferation Alternative Systems Assessment Program

Volume II: Proliferation Resistance

U.S. Department of Energy
Assistant Secretary for Nuclear Energy

June 1980

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DISCLAIMER

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ABBREVIATIONS AND ACRONYMS

AECL	Atomic Energy of Canada, Limited
AFR	Away-from-reactor
AIS	Advanced isotope separation
AR	At-reactor
AVLIS	Atomic vapor laser isotope separation
Bi	Bismuth
BWR	Boiling-water reactor
c	Centimeter
CANDU	Canadian Deuterium-Uranium
CFR	Code of the Federal Register
CIVEX	See Glossary
Co	Cobalt
Coprecal	See Glossary
D	Deuterium
DOE	Department of Energy
EURATOM	European Atomic Energy Community
EURODIF	See Glossary
F	Fluorine
FBR	Fast-breeder reactor
GCFR	Gas-cooled fast reactor
GWe	Gigawatt (electrical)
gm	Gram
H	Hydrogen
HEU	High-enriched uranium (nominally 90%, but always more than 20%, fissile)
HTGR	High-temperature gas-cooled reactor
HWR	Heavy-water reactor

I	Iodine
IAEA	International Atomic Energy Agency
INFCE	International Nuclear Fuel Cycle Evaluation
kg	Kilogram
kmp	Key measurement points
kw	Kilowatt
LEMUF	Limit-of-error of the material unaccounted for
LEU	Low-enriched uranium (nominally 3 to 5%, but always less than 20%, fissile)
LMFBR	Liquid-metal fast-breeder reactor
LWBR	Light-water breeder reactor
LWR	Light-water reactor
m	Meter
ma	Milliamp
MBA	Material balance area
MLIS	Molecular laser isotope separation
MC&A	Material control and accounting
MOX	Mixed oxides (of uranium and plutonium)
MUF	Material unaccounted for
MWe	Megawatt (electrical)
MWth	Megawatt (thermal)
N	Nitrogen
NASAP	Nonproliferation Alternative Systems Assessment Program
NDA	Nondestructive assay
NNWS	Nonnuclear weapons state
NPT	Treaty on the Non-Proliferation of Nuclear Weapons
NRC	Nuclear Regulatory Commission
NWS	Nuclear weapons states
O	Oxygen

PSP	Plasma separation process
PIPEX	See Glossary
Pu	Plutonium
PUREX	See Glossary
PWR	Pressurized-water reactor
R&D	Research and development
rem	Roentgen equivalent man
SSCR	Spectral-shift-controlled reactor
SWU	Separative work units
t	Metric ton
U	Uranium
UCOR	See Glossary
URENCO	See Glossary

1. OVERVIEW: PROBLEM, ASSESSMENT APPROACH AND PROCEDURE, AND SUMMARY OF ASSESSMENTS AND RECOMMENDATIONS

The international community has developed a regime designed to provide substantial protection against the proliferation of nuclear-weapons (or nuclear-explosive) capabilities. Although currently deployed once-through nuclear-power systems do not readily lend themselves to proliferation, they may facilitate the acquisition of the materials, facilities, and expertise necessary to develop nuclear weapons. And in the future, more widespread or advanced nuclear-power systems may more readily lend themselves to proliferation. For as these systems evolve, their abuse, whether overt or covert, may provide a more attractive route to nuclear-weapons capabilities than other routes, or it may enhance them significantly. The decision to obtain nuclear weapons, while affected by technological considerations, is basically a political one, whether made at a national or subnational level. It is important, therefore, to ensure that nuclear-power systems, as they evolve, do not make this decision an easy one.

Although many factors affect decisions about the acceptability, role, and timing of the development and deployment of various nuclear-power fuel cycles, they are treated elsewhere in this report. The purpose of this volume is limited to an assessment of the relative effects that particular choices of nuclear-power systems, for whatever reasons, may have on the possible spread of nuclear-weapons capabilities. This volume addresses the concern that non-nuclear-weapons states may be able to initiate efforts to acquire or to improve nuclear-weapons capabilities through civilian nuclear-power programs; it also addresses the concern that subnational groups may obtain and abuse the nuclear materials or facilities of such programs, whether in nuclear-weapons states (NWS's) or nonnuclear-weapons states (NNW's).

Accordingly, this volume emphasizes one important factor in such decisions, the resistance of nuclear-power systems to the proliferation of nuclear-weapons capabilities. In this context, proliferation resistance is the capability of a nuclear-power system to inhibit, impede, or prevent the abuse, that is, the diversion, of associated fuel-cycle materials or facilities from civilian to military uses. It may be achieved through a combination of the technical and institutional features of the system, to the detriment of would-be national or subnational proliferators. However, discussions of proliferation resistance customarily identify the materials or facilities most vulnerable to abuse and consider technical and institutional measures

that, developed over time, might be employed to reduce these vulnerabilities and thus increase the proliferation resistance of these fuel cycles. This volume treats proliferation resistance in this fashion. While this volume considers both technical and institutional measures, it assesses only technical measures; Volume VII assesses institutional measures.

The rest of this chapter provides an overview of the problem, describes the approach and procedure for assessing proliferation resistance, and presents a summary of assessments and recommendations.

Chapter 2, Assessment of Civilian Nuclear Systems, examines fuel cycles, research reactors, and critical facilities. The assessment specifies the proliferation features and activities, and the national contexts in which the fuel cycles are significant. The national context is the situation in which the proliferation attempt may be made. It includes consideration of the fuel-cycle facilities deployed; the number and quality of the weapons sought; the safeguards, protective measures, and other institutional provisions that may apply; and the general nature and level of the technical, financial, and political means that a nation has at the time it faces a decision on weapons. Other or alternate systems are examined in the same way.

Chapter 3, Assessment of Associated Sensitive Materials and Facilities, discusses sensitive materials and facilities in more detail. It deals with the accumulations of spent fuel and plutonium, and with different existing and possible enrichment technologies and reprocessing methods, only a few of which are in commercial use.

Chapter 4, Safeguards for Alternative Fuel Cycles, describes safeguards and examines International Atomic Energy Agency (IAEA) and U.S. safeguards and their application to the different fuel-cycle facilities.

1.1 THE PROBLEM

1.1.1 Is There a Problem?

The relevance of civilian nuclear-power programs to proliferation centers on the access that they may provide to weapons-usable materials, facilities, or expertise, and on the significant influence that access may have both on the decisions of nations or subnational groups to seek nuclear weapons and on their ability to implement such decisions. Despite this common focus, there is a diversity of opinion about the likelihood of proliferation through the abuse of civilian nuclear-power programs or the relative importance of such programs to the proliferation problem. For all nuclear-weapons programs to date have developed from nuclear materials and facilities not subject to international safeguards. Even if other routes were more efficient or quicker, easier, and cheaper than abuse of the fuel cycle, it does not follow that no nation would abuse the fuel cycle. One premise of this assessment is that, even though there are several routes to a nuclear-weapons capability, uncertainties about the perceptions of other nations, the differences in their situations, and the seriousness of proliferation by any route are so great that reducing the risk of proliferation by all routes, including civilian nuclear-power programs, is essential to the overall management of the problem.

Another premise is that abuse of the fuel cycle cannot be regarded as a trivial part of the problem; in fact, the abuse of the fuel cycle may be one of several attractive routes to a potential proliferator. Pakistan is a case in point. Zulfikar Ali Bhutto, the recently deposed leader of Pakistan, is reported to have stated that a safeguarded reprocessing plant was to be his means of acquiring a nuclear-weapons capability (The Washington Post, December 8, 1978, p. A1). More recent events in Pakistan, including an effort to construct a clandestine enrichment plant, apparently reflect a national determination to acquire such a capability and thereby enhance the credibility of Bhutto's statement (The Washington Post, April 9, 1979, p. A1). Clearly, the idea of abusing a nuclear-power system cannot be casually dismissed and has long been recognized as a possibility. The result is the current international regime of agreements, treaties, guidelines, and the international safeguards system.

1.1.2 What is the Problem?

The problem of proliferation is the danger posed by the movement toward or acquisition of a nuclear-weapons capability by a nation or subnational group presently without it. This danger is aggravated by the similarities of nuclear materials, facilities, and processes involved in developing nuclear-power and nuclear-weapons capabilities. In turn, these similarities can make the real purpose of a nuclear development ambiguous throughout much of the process. The decision to acquire a nuclear-weapons capability may be faced at any time in the course of this development and is influenced by three primary considerations. These are the supply of materials, facilities, and expertise; the demand for weapons; and the perceptions of the political and military risks entailed, that is, the risk of detection and response by one or more nations, or by the international community as a whole.

In facing the complex decision to move toward or to acquire nuclear weapons, a nation or a subnational group is likely to choose a course of action that ensures the greatest chance of success at the lowest risk of detection and response. Where there is a choice, it is between an independent military capability and an abuse of civilian facilities, which include nuclear-power, research and development (R&D), and critical facilities. As the development of a nuclear-power program overlaps the development of a nuclear-weapons program and is recognized as legitimate, so a decision to acquire a nuclear-weapons capability can be implemented with reduced political and military risks. If all actions are legitimate, the risks are minimized because all actions are justifiable in terms of nonmilitary purposes.

For this reason, proliferation resistance focuses upon the degree to which overlap between military and civilian nuclear-power programs may be prevented or reduced. Where the two programs do not overlap, the distance between a civilian nuclear-power program and the possession of nuclear weapons is appropriately measured by the additional resources and time involved after a nation makes a commitment which violates agreements or conventions of international behavior. The nature of those resources and the time necessary to marshall them productively help determine the likelihood of exposure to risk that a nation runs in moving toward or acquiring a nuclear-weapons capability from a starting point in a civilian nuclear program.

This starting point is crucial, and the basis for controversy about the possibilities for proliferation through the abuse of a civilian nuclear-power program. On the one hand, the resources required to develop an independent military program may be substantially less than those required to develop a civilian nuclear-power fuel cycle. (For instance, it is within the capabilities of many nations to construct a heavy-water or graphite-moderated reactor fueled by natural uranium and to construct a reprocessing plant to produce a few weapons per year. The Office of Technology Assessment estimates the cost and time required from the start of design through plutonium metal production in these facilities to be about $100 million and five years.) On the other hand, the resources required to develop an independent military program may be much more than those required to abuse an existing civilian program. Perhaps more important, developing an independent military program can involve a longer time for detection and response by one or more nations, or the international community as a whole, than moving to nuclear weapons from a civilian program. In fact, it may be easier for a decision to be made as the result of a sequence of incremental moves which have, or appear to have, civilian objectives rather than all at once for specifically military purposes. Moreover, the potential for proliferation through the fuel cycles can be unclear to domestic as well as foreign observers and does not even have to be in mind when a nation chooses a nuclear-power program. As a result, there can be drift, whether deliberate or inadvertent, toward easier routes to a nuclear-weapons capability.

The period of time after which movement toward obtaining weapons is clearly distinguishable from legitimate civilian nuclear activity is critical. For then a nation runs a risk of detection and response; and only if the potential proliferator anticipates such a risk can it have a deterrent effect. This exposure time depends on perceptions about when an activity, even if legal, is politically unacceptable and violates international norms.

Accordingly, such a convention needs to address the ambiguities which arise because all nuclear-power fuel cycles involve either "sensitive" (weapons-usable) material or a potentially "sensitive" facility (one that can produce, or can easily be modified to produce, weapons-usable material) that is in the system. Ambiguities may also arise about an out-of-system facility, which is not part of the nuclear-power fuel-cycle system under consideration. Such a facility may be used for another fuel cycle or other civilian purposes, like producing isotopes for medical or biological uses, or it may be used for nuclear-weapons purposes, in which case it is called a "dedicated" facility. In short, the mere fact that a facility is out-of-system does not identify it as military or prove that its purpose is dangerous or proscribed, but it does make the purpose of the facility ambiguous until its actual purpose can be

established. The potential for abuse of sensitive facilities when they are in-system or their inherent ambiguity when they are out-of-system defines the proliferation risk of nuclear-power fuel cycles.

Although no nuclear-power fuel cycle is completely free of proliferation risks, fuel cycles can differ significantly in their degree of resistance to abuse. Their relative proliferation resistance depends both on the technical features and activities of the fuel cycles and on the institutional arrangements and political situations under which they are used. At the present time, states can have material directly usable in nuclear weapons without having to make the decisions or to take steps to implement them which are unambiguously directed toward developing a nuclear-weapons program, in contrast to a situation in which dedicated facilities have to be built.

The goals of the task at hand to reduce the risks of proliferation through civilian nuclear-power programs are threefold. The first is to secure agreement, if possible, on the conditions and controls under which civilian nuclear activities are acceptable. The second is to ensure that no civilian starting points be easy, that the exposure time be long, and the detection system be effective. The third is to ensure that when nations undertake to develop a nuclear-power program, they recognize in advance that its abuse for nuclear-weapons purposes is too risky politically or militarily because the adverse consequences are too great to accept.

The purpose of the current international safeguards regime is to deter the abuse of civilian fuel-cycle materials or facilities through procedures which ensure timely detection, on the assumption that such detection could have unacceptably high risks. International safeguards are intended to warn of an attempt to develop nuclear weapons from safeguarded materials or facilities. They are also intended to provide evidence that nuclear weapons had been prepared in violation of nonproliferation obligations without relying on the detection of nuclear-weapons (or nuclear-explosive) tests.

To achieve this purpose, the regime must make the risk of detection great enough to make it easier for a potential proliferator to withdraw from international safeguards or establish an independent military program than to abuse a civilian nuclear program. At the same time, the regime must make the level of assurance provided for different components of different fuel

cycles credible by considering the safeguards efforts required to provide the necessary level of assurance. For the risk of detection and the credibility of safeguards efforts would provide very little assurance in a hypothetical situation in which all users of nuclear energy had direct access to nuclear-weapons-usable materials or facilities, since it would be very difficult to verify all of their activities.

Despite the intent of the current international safeguards regime and its contribution to the proliferation resistance of civilian nuclear programs, the vulnerabilities of the fuel cycle remain a matter of continuing and significant concern. This volume assesses these vulnerabilities, both technical and institutional, so that the proliferation risks of the different fuel cycles and fuel-cycle systems may be reduced as civilian nuclear-power systems are developed.

1.1.3 How Urgent is the Problem?

The problem is made urgent by trends in the development and deployment of different fuel cycles and nuclear-power systems, and by political developments in some parts of the world. The current regime is characterized largely by once-through systems, in which the predominant reactor is the light-water reactor (LWR) and in which enrichment services are provided by a few states. Spent fuel is being held in interim storage, most of it at radiation levels that make reprocessing possible only with facilities which presently exist in few nations. In fact, there is only one large-scale plant currently in operation to reprocess spent LWR fuel, although smaller plants also exist. A variety of constraints, political and institutional, on international behavior has combined to keep the proliferation of nuclear weapons well within the limits some had projected. These constraints include alliance relationships, the current international regime controlling civilian nuclear activities, and an international climate in which the development of nuclear weapons is increasingly viewed as not being a legitimate activity.

But there is a growing concern that there are at least two trends toward greater proliferation risks. The first of these is that more nations are acquiring access to sensitive materials and facilities. Several nations are planning or constructing enrichment facilities for greater assurance of fuel supply than they believe that they can obtain from the few nations that now

supply enrichment services. Some nations have stated that the need to dispose of the growing amount of spent fuel in interim storage is one consideration in their plans to build and operate reprocessing facilities. Some nations with uncertainties about the longer-term availability of uranium resources and with a desire for national control over the fuel cycle are beginning to develop fast breeders and their associated fuel-cycle components. The second trend is that increasing numbers of these nations, may have incentives to acquire or to consider shortening the time to acquiring a nuclear-weapons capability. Not all of these nations have indicated a willingness to forego nuclear weapons or nuclear-explosive devices by acceding to the Non-Proliferation Treaty (NPT). Both the dynamics of evolving nuclear-power systems and changing political realities require that the existing regime which controls civilian nuclear activities be reassessed to find ways to strengthen it against the dangers of nuclear proliferation.

1.2 ASSESSMENT APPROACH AND PROCEDURE

1.2.1 Assessment Approach

The scope of the NASAP proliferation assessment has been deliberately set to try to ensure an analysis and evaluation that, at a minimum, reflects the breadth of the proliferation risks associated with the various fuel cycles in dealing with both technical and institutional factors and in taking into account the uncertainties of the evolving situation. However, while NASAP recognizes that the absolute risk of proliferation is an important nuclear-power policy issue in itself, this assessment focuses on the relative differences among the fuel cycles. The goals toward which the assessment strives have been defined in a series of statements of ideals. These statements should be viewed as guidelines, not criteria, for a definitive study of the problem.

The assessment should recognize the complexity of the proliferation problem and take into account the evolving situation. Relative proliferation resistance of various nuclear materials or facilities involves not only the technological characteristics of the materials, facilities, and activities involved, but also the framework of international institutions, national policies, and future contingencies which may apply in each nation. Moreover, account must be taken of the relative stages of development of different fuel cycles as well as the evolutionary nature of technical and institutional

aspects of the fuel cycles. Relative risks change with the evolution of new technologies as well as with new political and institutional contexts.

The factors involved are large in number, diverse in kind, and dynamic in time. Some of these factors can be quantified, but many of the important factors of proliferation resistance such as institutional arrangements cannot be quantified. Even those factors that can be quantified are not commensurate. Thus, valid assessments of proliferation resistance of nuclear-power systems cannot be made with a simple, universal formula or methodology. There is no "proliferation resistance index." Nevertheless, the general assessment factors that are used in NASAP have gained a wide degree of acceptance.

It is important to avoid overgeneralization of conclusions. In fact, this chapter reflects this complexity in developing its major observations, not by quantitatively ranking fuel cycles, but by identifying the particular judgments that must be made by taking into account technical and institutional aspects of proliferation resistance. For example, the additional deterrence gained by spiking is set against the difficulty in accounting for bulk material, but no conclusion is drawn about the overall desirability of that method of deterrence.

The assessments should take into account the possible effects of nuclear-power programs on nuclear proliferation decisions in a wide range of political, military, and technological situations which may arise in various countries over the next half century. A particular set of representative scenarios (described below) was used in conducting proliferation resistance analyses to identify the proliferation vulnerabilities of nuclear fuel-cycle systems and their alternatives, and the possible improvements that could be made. These analyses were further tested and refined by considering both wider-ranging and more specific scenarios suggested in discussions of hypothetical situations. For example, the relative ease of obtaining nuclear weapons-usable material in one country might contribute to changes in national policies about acquiring a nuclear-weapons capability either in that country or in other countries. The representative scenarios involved both nations and subnational groups, and activities both covert and overt. Four representative scenarios are described below:

- A nation makes a deliberate decision to make nuclear weapons by the use of a separate military fuel cycle. This route is often

referred to as the "independent path" or the use of "dedicated" facilities. Such a decision is a political matter and cannot be prevented by technological or institutional measures designed to prevent the abuse of civilian nuclear-power systems. What kind of nonproliferation commitments had been made, however, would be important. Moreover, military fuel-cycle facilities could be based on the replication of civilian fuel-cycle facilities so that the agreements under which civilian technology is transferred from one nation to another are also important. This scenario is relevant to the consideration of research reactors and critical facilities (Section 2.3) and of the relationship between civilian and military nuclear-fuel cycles (Section 2.4). It is implicit in the discussions of enrichment and reprocessing (Sections 3.1 and 3.3, respectively).

- A nation makes a deliberate decision at some point in developing a nuclear fuel cycle to make nuclear weapons by abuse of its nuclear-power fuel-cycle facilities. This is the principal class of proliferation scenarios assessed. A nation may attempt to use its nuclear fuel-cycle facilities to produce weapons-usable material in either a covert or overt manner. The attempt might be made in the face of nonproliferation commitments and international safeguards or following abrogation or withdrawal from such commitments. Resistance to covert abuse is primarily a function of the chance of detection, which will depend on the efficacy of the international safeguards regime if it is in effect in the country and on the credibility and timeliness of international responses to detection. However, the resistance to overt abuse is primarily a function of the technical and institutional features built into the fuel cycle and its facilities. In any case, the principal deterrent is the likely reaction of key members of the international community.

- A subnational group attempts to acquire nuclear material by theft or by seizure of nuclear-power fuel-cycle facilities. Prevention of theft and any other subnational abuse of the fuel cycle is the responsibility of the domestic safeguards and physical security regime enforced by national governments. However, where technical or institutional measures are introduced because of the proliferation risk, these also may make theft more difficult.

- There is also a potential overlap between the national and subnational routes, since material stolen by a subnational group could subsequently be used by a nation for proliferation; or one nation could underwrite a subnational threat against another nation; or the group could be within a government and, without its approval, divert materials and facilities to weapons purposes.

These latter three scenarios were considered in the assessments of the nuclear-power fuel cycles and nuclear facilities in Sections 2.1, 2.2, and 2.3 as well as in the generalization to the complexity of the real world in Section 2.4.

In addition, the evolving situation was considered in light of the information on worldwide plans for nuclear-power development. These plans reflect reasonably firm commitments through the mid-1980's; thereafter, they are increasingly tentative because of technical, economic, and political uncertainties; and after 2000 only general trends merit discussion.

The assessment procedure should develop a general framework within which the analyses can be conducted. Because of the complexity of the problem, a baseline, or benchmark, for the assessments must be identified. The approach taken is to treat three generic nuclear-power systems and ancillary research activities as simplified, isolated entities. The three systems are designated by the names of their fuel cycles, once-through, recycle, and fast breeder. Research reactors and critical facilities are examined separately. Even though there is no "proliferation resistance index," the NASAP factors have been used in the assessments, and, instead of criteria directly related to these factors, a benchmark nuclear-power system has been used for purposes of comparison. This benchmark is the LWR once-through fuel cycle, in which spent fuel is discharged into interim storage. This system is the one most widely used in the world today; however, its use as a benchmark does not imply that its absolute risk is acceptable. The level of acceptable risk itself is a matter of controversy. In this report, the benchmark itself has been assessed, and desirable improvements to it have been identified.

The assessments should not look at fuel cycles in an abstract sense; rather, particular realizations should be analyzed and various alternatives examined in relation to technical and institutional considerations. The approach taken is to treat a reference system in each generic system and then to treat alternative systems which differ in specific ways from the reference system. Moreover, in the case of a particular fuel cycle, two kinds of national deployment are considered. One kind, which requires external enrichment or reprocessing services, involves the national deployment of the reactor and intermediate spent-fuel storage facilities; the second kind, which includes enrichment or reprocessing facilities, involves the national deployment of all fuel-cycle facilities.

The assessments should concentrate upon identifying the potential proliferation features and activities of the various fuel cycles and examine possible technical and institutional improvements and their effects. The parts of a particular fuel cycle most sensitive to proliferation depend on the nature of the threat. In the case of covert national diversion, facilities for processing bulk material may be the most sensitive part. In the case of overt national diversion, the storage of separated plutonium is probably the most sensitive part of the fuel cycle. In the case of subnational diversion, transportation can be considered the most sensitive part.

1.2.2 Assessment Procedure

The assessment procedure used characterizes the proliferation resistance of nuclear-power systems in terms of the activities necessary to acquire weapons-usable material. When separated from other materials, both uranium (U) enriched to high concentrations in the isotopes U-235 (more than about 20%) or U-233 (more than about 12%) and plutonium (Pu) are considered to be nuclear weapons-usable materials, whether in oxide or metallic form. (Uranium enriched to 90% or more is often used--and is so used in this volume--for estimating the relative enrichment requirements for nuclear-weapons purposes. Moreover, while an independent military program to construct nuclear weapons may be considered likely to avoid the use of commercial-grade plutonium containing a significant amount of the higher plutonium isotopes, such plutonium might be used for weapons purposes in certain circumstances. As used in this volume, plutonium means total plutonium, that is, all plutonium isotopes.) The activities examined include the possible removal of materials from the fuel cycle, the modification of an in-system facility to produce these materials, or the construction of an out-of-system (and possibly dedicated) facility for conversion of these materials into a weapons-usable form, and the conversion itself. These required activities and the associated possibilities for detection and deterrence depend both on the technical features of the fuel cycle under consideration and on the safeguards, protective measures, and other institutional provisions that may apply.

The central question to be answered about the proliferation resistance of a nuclear-power system is how easy is it to decide to abuse it or to implement a decision to abuse it. The answer to this question depends upon the answer to three specific questions:

- What resources and efforts does abuse require at the national and subnational level?

- How long will it take?

- Will it be detected, and, if so, what can be the consequences?

The assessment of proliferation resistance depends substantially on the proliferation scenario. For example, a particular isotopic enrichment technique may be hard to implement for a country with a well-developed technological base and experienced personnel, much harder for a less-developed country, and essentially impossible for a subnational group. Moreover, the resources required depend on the number and quality of the nuclear weapons sought, and the significance of this resource requirement as a barrier to abuse depends on the situation of the proliferator. Because of the great number of possible combinations of systems, activities, and situations, only a few representative possibilities are treated explicitly.

These and similar considerations have led to the development of a check list to be used in the assessment. Many, but not all, of these considerations are predominantly technical in nature and are descriptive of the fuel-cycle materials, facilities, and technologies. Some of these are intrinsic to the nature of the proliferation activities required, and some are extrinsic, dealing with the international scale and spread of fuel-cycle activities. These considerations are listed in Table 1.2-1. They are the basis for three major groups of assessment factors used in performing the assessments. These groups are:

- Resources required--the technological base, personnel, and financial resources needed for the specified proliferation activities in light of their inherent difficulty.

- Time required--the approximate times needed for the specified proliferation activities, including preparation, removal, and conversion.

- Risks of detection--the chances and consequences of detection of the proliferation activities, including preparation, removal, and conversion, and the possible timeliness of detection.

Estimates of these factors rely upon many diverse variables which change over time, some of which can be quantified to some extent and many of which cannot. Accordingly, the assessments using these factors are presented as qualitative

Table 1.2-1. Basic Considerations

General Factors

(i) The number of sites with significant quantities of sensitive nuclear materials

(ii) The need for storage and transport of these materials

(iii) The quantity of these materials

Form of the Material

(iv) The accessibility (radiation level) of these materials

(v) The quality (isotopic mixture and chemical form) of the materials

(vi) The resources required by different routes to prepare for, remove, and convert these materials to nuclear-weapons purposes

(vii) The times required by these activities

Nature of the Facility

(viii) The resources and time required by different routes to adapt the facility to nuclear-weapons purposes

(ix) The resources and time required for covert replication of fuel-cycle facilities

Degree of Protection

(x) The likelihood of detection of abuse

(xi) The amenability to institutional arrangements

(xii) The amenability of the materials and facilities to safeguarding

Evolution

(xiii) The evolution of programs with time in countries at different stages of deployment and development

discussions which focus on the important considerations but which do not usefully lend themselves to methodological tabulations or quantitative rankings.

The resulting assessments suggest a range of possible technical and institutional measures to increase the proliferation resistance of the fuel cycles. The effectiveness of possible technical and institutional improvements is discussed briefly in this chapter. But because the proliferation resistance of institutional improvements is dependent on their specific nature and on other and broader considerations such as their acceptability, assessment of their nonproliferation effectiveness is deferred to Volume VII, which deals with international deployment. In Volume VII, each measure is assessed in terms of its effectiveness in increasing proliferation resistance, its likely time to develop and apply, and any other significant advantages and disadvantages that it may have. Also deferred to Volume VII are broader considerations important to proliferation risks, which range from a fuller account of the resources required for proliferation activities to the political commitments required as well, and the consequences of detection that might result from the unilateral or multilateral application of sanctions. Analyses of the economics of various fuel cycles should, of course, also take into account the probable costs and timing of proliferation-resistance measures, and these analyses, too, are presented in other volumes.

1.3 SUMMARY OF ASSESSMENTS AND RECOMMENDATIONS

The assessments of the proliferation resistance of various fuel cycles involve the simultaneous consideration of many variables, most of them unquantifiable, and an awareness of the evolutionary nature of the fuel cycles and the evolutionary nature of nuclear programs in different countries. Accordingly, these assessments cannot be purely technical in nature, nor is there a proliferation resistance "index" that can be applied. For instance, it has not been found useful to try to rank the three generic fuel cycles or their respective reference systems and alternatives quantitatively. Rather, what has been done has been to identify promising combinations of fuel cycles, and technical and institutional improvements for current fuel-cycle activities and deployments.

This conclusion summarizes assessments and recommendations, neither of which are necessarily based entirely upon technical analyses. The assessments of

the proliferation resistance of various fuel cycles involve judgments about nontechnical as well as technical factors of the fuel cycles. The recommendations, while taking into account these assessments and technical analyses, also identify technical and institutional measures which might improve the proliferation resistance of various fuel cycles and fuel-cycle systems. It is important to note the difference: while technical factors are assessed here and in this volume as a whole, institutional factors are assessed, not here, but in Volume VII.

The most important conclusions of the NASAP proliferation resistance assessments are:

- All fuel cycles entail some proliferation risks; there is no technical "fix" that will permit operation of a nuclear-power fuel cycle with material that cannot be diverted to use in nuclear weapons or that will preclude a determined owner-operator from designing a proliferation strategy.

- The LWR fuel cycle with spent fuel discharged to interim storage, however, does not involve directly weapons-usable material in any part of the fuel cycle and is a more proliferation-resistant nuclear-power fuel cycle than other fuel cycles which involve work with HEU or pure plutonium.

- Substantial differences in proliferation resistance also exist between the fuel cycles if they are deployed in NNWS's. Some of these differences are technical in nature (e.g., no reprocessing in once-through fuel cycles), and some result from institutional arrangements (e.g., limited deployment of existing international enrichment services).

- On the other hand, with the progressive introduction of technical and institutional measures to improve proliferation resistance, these differences may be reduced by the time the fuel cycles eventually come into widespread use. The differences will remain until the necessary improvements have been made, not only in newer facilities, but also in older ones.

- The vulnerability to threats by subnational groups varies between fuel cycles; whereas once-through fuel cycles are susceptible to only the most sophisticated threats, closed fuel cycles are vulnerable to a wide range of threats.

The other conclusions are grouped by the time sequence of the decisions which nations face about their civilian nuclear activities, legitimate decisions about ensuring the availability of nuclear power now and in the future. Conclusions about current deployment, that is, about the commercially deployed LWR and heavy-water reactor (HWR) power-supply systems; research reactors; and R&D activities such as pilot-scale reprocessing and enrichment facilities that are now in place in anticipation of future needs are discussed first. In the near term, decisions affecting proliferation risk that may improve the current regime and that may influence the choice between continuing reliance on once-through fuel-cycle systems or continuing movement toward implementing closed fuel-cycle systems will be made. In the longer term, decisions will address the increasing risks resulting from continued reliance on once-through systems, improvements in the regime to reduce the risks of closed cycles, and the prospects that advanced reactor concepts could contribute to controlling proliferation risks.

1.3.1 The Existing Situation

The current regime applied to once-through systems (which do not include national reprocessing facilities) has contributed to limiting proliferation. The civilian nuclear-power cycle has been separated from military uses by means of bilateral and multilateral agreements for cooperation, in which assistance is provided by suppliers in return for a guarantee to use the assistance furnished only for peaceful uses and acceptance of nonproliferation conditions. Compliance with these commitments is verified by the IAEA safeguards system. This process for establishing a general climate of opinion against the spread of nuclear explosive capability is supported by the accession by over 110 nations now party to the NPT. All nuclear material in the peaceful activities of the NPT parties who are NNWS's are subject to IAEA safeguards. In addition, Britain, France, and the U.S. have volunteered to place their peaceful nuclear activities under safeguards. When all the civilian nuclear activities in a nation are subject to IAEA safeguards, whether as a result of accession to the NPT or otherwise, the nation is sometimes referred to as being under "full-scope" safeguards.

- Given the current relative availability of detailed process information and trained personnel, the isotopic barrier to the production of weapons-usable material from fresh fuel appears greater than the chemical or radiation barrier to the production of weapons-usable material from spent fuel. But this difference could change with time, particularly if enrichment facilities become widespread.

- The LWR fuel cycle with spent fuel discharged to storage has relatively high barriers to proliferation at this time, but it does have vulnerabilities. The two greatest proliferation risks would arise:

  - If the potential proliferator had an enrichment plant, or, since enrichment services are now supplied by only a few nations,

  - If the potential proliferator had an out-of-system reprocessing facility to recover weapons-usable plutonium from spent fuel.

- Facilities for closed fuel cycles potentially increase proliferation risk because plutonium would appear in weapons-usable form and in forms that are relatively easy to exploit for weapons purposes. Without deployment constraints and suitable institutional arrangements, plutonium would appear in substantial and widespread inventories in bulk forms, which are inherently difficult to safeguard.

- Fresh-fuel inventories for many research reactors are a potential proliferation risk because they contain chemically separable high-enriched uranium (HEU) suitable for fabrication in nuclear weapons.

- All enrichment technologies can be used to produce HEU. They differ significantly, however, in the difficulty, cost, time, and visibility of modifying commercial plants or in the time required to produce HEU in them or in their use in dedicated facilities. Of currently deployed technologies, the proliferation risks of gas centrifuge processes appear greater than those of gas diffusion.

1.3.2 Near-Term Considerations

Although the current regime applied to once-through systems (which does not include national reprocessing facilities) has contributed to limiting proliferation, there are trends toward increasing proliferation risks. One is that commensurate with the expansion of nuclear power, recently projected by the International Nuclear Fuel Cycle Evaluation (INFCE) to grow by more than ten times outside the U.S. before 2000, a greater geographic dispersal of supporting sensitive fuel-cycle facilities may result. Another is that several nations have indicated the start of a transition from today's once-through fuel cycle, some to recycle, and several to fast breeders.

A corresponding growth in supporting fuel-cycle facilities and greater geographic dispersal can be expected. Nearly all enrichment and reprocessing plants included in currently stated plans are scheduled to begin operation by 1990 or somewhat later. The continuation of the current trend in some nations with less advanced nuclear-power programs will most likely depend on recycle or fast-breeder developments in the major supplier countries. Meanwhile, some nations are keeping their options open by gaining experience with laboratory or pilot-scale sensitive facilities even though they do not have definite plans regarding recycle or fast-breeder fuel cycles.

In short, planning to strengthen the current regime against proliferation risks must recognize the following five findings about alternative fuel cycles:

- Continued reliance on LWR's may call for expanded enrichment capacity. While the development and demonstration of advanced isotopic separation (AIS) technologies may discourage the spread of centrifuge enrichment technology that now appears relatively easier to utilize for production of HEU, their future deployment should be limited.

- Under any realistic deployment schedule for the foreseeable future, the amount of plutonium and the rate of its increase is not likely to differ very much among any of the various fuel cycles. However, these fuel cycles differ greatly in the form in which plutonium appears and in the extent to which it can be controlled and safeguarded. The recycle system involves the production and processing of separated plutonium in reprocessing and fabrication facilities, and its presence in storage and transit.

- While these same difficulties apply in principle to fast-breeder systems, major fast-breeder programs are expected to remain confined for several decades to a few nations. The spread of breeder R&D activities, however, continues to be an area of concern.

- A reprocessing technique that cannot be used directly or cannot be modified readily to produce separated plutonium has not been demonstrated. Prospective techniques like pyrometallurgy have been provisionally identified on the basis of preliminary analysis as possibly offering greater diversion resistance for reprocessing fast-breeder fuels.

- No nuclear fuel cycle which can be commercially deployed in the next few decades would offer more proliferation resistance than

that associated with realizations of the LWR once-through fuel cycle, in which spent fuel is safeguarded in interim storage facilities and enrichment services are provided by the existing suppliers. But concurrently, pressures may grow to develop independent, alternative, less proliferation resistant fuel cycles.

To relieve pressures on existing spent-fuel storage, commitments for additional spent-fuel storage arrangements will be needed by the early-to-mid-1980's, regardless of decisions about reprocessing. But as accumulations of spent fuel continue to increase, the pressure to do something, including the possibility of reprocessing, will also increase. Spent fuel can be effectively safeguarded, but there remain substantial technical and institutional issues associated with an international spent-fuel storage regime to be resolved. For example, issues about facilities under international auspices would include the incentives for joining the regime, the location of facilities, the type of long-term arrangements envisioned, and the development of acceptable criteria for the release of stored fuel.

Plans for enrichment, including expansion at existing plants, are expected to result in supply exceeding demand into the 1990's. Moreover, multinational enrichment ventures can provide the opportunity for participation as owners but not operators, as some do now, a feature likely to contribute to nonproliferation by reducing the spread of technology and the need for new plants. Nevertheless, technically and institutionally more effective safeguards are required for these existing and planned facilities. Moreover, there are ongoing R&D activities in several nations. In the absence of a clear need, such activities should be discouraged or at least brought under multinational auspices.

Substantial progress has already been made in the development and commercialization of fuels of lower enrichment for research and test reactors. There are over 150 such reactors operating worldwide which use weapons-grade uranium. Such HEU poses potential proliferation and terrorist threats. This problem can be partially mitigated by safeguards and enhanced physical security. But with substantial quantities of HEU moving in international commerce, 5 metric tons a year, additional improvements to the international regime are required. Accordingly, a program to convert these reactors to the use of fuel of lower enrichment (eventually down to 20% enrichment) has been launched. Future sales of such reactors should be based on a clear demonstration of need. In addition, cooperative arrangements for using

existing research centers could be explored as an alternative to building new critical facilities, which use HEU or plutonium, or large research reactors, which produce significant quantities of plutonium.

Measures are also required for bringing under the international regime plutonium-related research, development, and demonstration activities which are currently ongoing in several nations and which are aimed at the next generation of nuclear technology. Reprocessing capabilities under national control (including the prior operation of pilot facilities) now exist in more than ten nations. Schemes for placing stocks of separated plutonium under international management or supervision could serve to reduce the risks of proliferation, but the development of acceptable release criteria will be difficult.

If currently stated plans are realized, demands on nonproliferation institutions will increase dramatically in the next few decades. In response, measures which would respond to legitimate desires for security of supply and which would significantly improve the proliferation resistance of civilian nuclear activities have been identified. Such measures for the near term, when few recycle or fast-breeder systems will be commercialized, and those for different fuel-cycle development choices, can be summarized as follows:

- Wider acceptance of international safeguards on all civilian nuclear activities (full-scope safeguards) and of the NPT and other treaties (e.g., Treaty of Tlatelolco).

- Application of improved safeguards measures already shown to be technically feasible, in particular, measures to provide timely warning of overt abuse or covert diversion of spent fuel either upon discharge from the reactor or in storage. (Measures could include systems with remote, near-real-time surveillance capability and more frequent inspections. The CANDU reactor requires specialized verification systems for on-line refueling.)

- Development of effective safeguards systems now in the conceptual stage, for enrichment facilities, which themselves should be designed to facilitate safeguards.

- Continued reliance on existing suppliers of enrichment services including ventures under international or multinational auspices. Enrichment R&D should not be undertaken in the absence of a clear demonstration of need.

- o Adherence to export controls and the present suppliers' guidelines contained in the IAEA document INFCIRC/254.

- o Cooperative arrangements to ensure adequate spent-fuel storage, to provide the options for interim storage, and to leave open the decision regarding recovery of fissile materials or ultimate disposal. (Commitments for such arrangements will be needed by the early- to mid-1980's, and decisions will be needed soon regardless of decisions about reprocessing.)

- o Development of mechanisms for the international management or supervision of national stocks of separated plutonium.

- o Arrangements to minimize or avoid the storage or transport of undiluted plutonium.

- o Cooperative arrangements to share the use of existing large research reactors and critical facilities, and similarly to provide opportunities for R&D on breeders under international or multinational auspices.

- o Limitations on the use of materials in research reactors to enrichment levels which minimize the presence of weapons-usable material.

1.3.3 Longer-Term Considerations

Over the longer term, continued use of nuclear power will require an expansion of IAEA capabilities to keep pace with the expanded demand on the international safeguards system as the number, kinds, and scope of nuclear activities increase and as the amounts of fuel materials under national control also increase.

For the longer term, proliferation risks which depend upon the choices for the development of nuclear power can be identified.

Once-Through Systems

A continued dependence on once-through systems implies increasing stockpiles of spent fuel under national control, the need for additional storage capacity to counter increased pressures for national reprocessing, and more numerous but not different demands on the safeguards regime. It also implies an increased demand for enrichment and potential pressures for additional countries now engaged in R&D to develop production capacity. Moreover, the further deployment of enrichment technologies such as centrifuges under national control may enable nations to come close to a nuclear-weapons capability without having to make the unambiguous political commitment to acquire it.

The measures required to improve proliferation resistance in the near term will need to be expanded to deal with the longer-term proliferation risks arising from continued dependence on once-through systems. In particular, acceptable options for the ultimate disposition of spent fuel, whether by long-term storage, permanent disposal, or reprocessing, will have to be developed. In addition, the capacity of the international safeguards system will have to be expanded and strengthened to keep pace with increasing demand because of the increasing number of sites of nuclear activities and increasing stocks of low-enriched uranium (LEU) and natural-uranium feedstocks under national control.

Recycle and Fast-Breeder Systems

Recycle and fast-breeder systems are perceived by some nations as necessary to ensure long-term supplies of fuel for nuclear energy. The deployment of such fuel cycles results in the presence of plutonium in national facilities and in transit in a form more vulnerable to seizure and more difficult to safeguard than spent fuel or LEU, in significant commerce in plutonium-bearing materials in bulk form, and in reprocessing and mixed-oxide (MOX) fuel-fabrication facilities, which may be attractive for use in weapons programs in NNWS's. Because of the lower plutonium concentrations, recycle fuel may be somewhat more resistant in some respects than fast-breeder fuel. On the other hand, the widespread adoption of recycle in LWR's could lead to widespread commerce in plutonium-bearing materials and an increasing spread of plutonium separation facilities. At present, fast-breeder programs are confined to a relatively few nations with advanced nuclear-power programs.

The following conclusions about the prospects for improving proliferation resistance of closed systems over the longer term can be drawn:

- Technologically more advanced and comprehensive safeguards and physical security systems will be required to handle plutonium-bearing materials, particularly in bulk. These may include plutonium management systems such as inventory reduction as well as improved instrumentation for accounting, and containment and surveillance. However, such systems are likely to be costly to both the operator and the IAEA, and may require a politically significant degree of instrusiveness in national facilities. They may also involve measures that conflict with one another. For instance, the deliberate introduction of radiation barriers might enhance some containment and surveillance systems while curtailing the effectiveness of material accounting systems. The radiation adversely affects all accounting systems and may render some inoperative. Technological and safeguard decisions will involve sophisticated trade-offs in resolving such problems.

- Intensive R&D efforts particularly by the U.S. over several years have been directed toward developing potential solutions to these problems, and there is expectation that improvements in accounting, and containment and surveillance systems can be made to ensure technically effective safeguards, although no large-scale demonstration has been attempted.

- Realizations of a plutonium-based fuel cycle in which the nation concerned restricts itself to the deployment of the reactor alone and relies upon reprocessing or fabrication services supplied from a few large facilities are significantly less vulnerable to the risk of proliferation. However, the form of the plutonium and the conditions under which it is returned to the country are important.

  - An arrangement to minimize or avoid bulk materials, either plutonium metal, plutonium oxide, or mixed oxides (MOX) of uranium (UO_2) and plutonium (PuO_2), in storage or transit would be a significant improvement.

  - The addition of a radiation barrier may increase somewhat the time and additional out-of-system facilities required to produce weapons-usable material so that an international response can be developed.

  - Placing these few large facilities under some form of international or multinational arrangement could also be helpful in reducing proliferation risks.

- In the case of realizations in which all the nuclear facilities are deployed within a nation, none of the technical alternatives, including radiation barriers, can be very effective in preventing abuse, particularly with regard to overt diversion. Engineering features to reduce accessibility to plutonium and to facilitate safeguards may be helpful in reducing the risks of covert diversion. In addition, agreeing to minimize or avoid significant quantities of undiluted plutonium in any form in any part of the fuel cycle could provide an indication that a country stood in violation of it should undiluted plutonium be found.

- Resistance to subnational theft can be improved by the introduction of appropriate combinations of colocation of sensitive facilities, co-conversion, coprocessing, pre-irradiation, spiking, or partial processing, and engineering features to reduce accessibility to plutonium.

- The appropriateness of radiation barriers against a subnational group will depend largely on their effect on safeguards and physical protection, and economic and environmental considerations.

- The improvements contemplated in international safeguards, including improved plutonium management schemes, will also make subnational theft more difficult.

Many of these measures, however, will require time to resolve significant technical and institutional issues before they may be judged to be practicable.

Among these are the technical and institutional uncertainties surrounding the thorium cycle. The (denatured) thorium cycle offers the promise of providing an isotopic as well as a radiation barrier in fresh fuel in recycle systems since denatured fuels are unusable for nuclear weapons without isotopic separation.

Such enrichment technologies are likely to remain beyond the capacity of many nations for decades and beyond the capacity of most subnational groups for a very long time. The radiation barrier accompanying denatured U-233 fuel, although an industrial disadvantage, might enhance proliferation resistance somewhat.

With only reactors deployed in NNWS, denatured U-233 fuel would pose less of a proliferation risk than fresh plutonium fuel, even if this fuel were protected by a radiation barrier because the resources and technical difficulty required to overcome the isotopic barrier are greater than those for hot-chemical separation. The relative difference between the isotopic barrier and the radiation or chemical barrier could change. Denatured fuel would not, however, be as resistant as conventional LEU fuel. Although the thorium cycle would result in less chemically separable plutonium in spent fuel, there could be substantial amounts of plutonium and separated U-233 in recycle locations. Moreover, reactors could not be widely supported on denatured U-233 fuel at dispersed sites for several decades because that time would be required to build up adequate inventories. There is the possibility that the thorium fuel cycle can be designed in a symbiotic configuration in which the fast-breeder reactor (FBR) systems would produce the denatured fuel to be recycled into thermal reactors while consuming the plutonium generated by the thermal reactors. Arrangements based on this cycle would not realize all of the nonproliferation advantages, however, unless they were combined with the same kind of new institutional arrangements, such as secure, multinational energy centers and enhanced IAEA safeguards, that would also significantly, but to a lesser degree, improve the conventional uranium-plutonium recycle systems. The reason is that denatured U-233 fuel cycles also involve reprocessing and refabrication facilities. While arrangements like these also offer the promise of gradually reducing accumulations of the spent fuel from once-through systems, this promise is highly speculative at the present time. Moreover, the more complex the systems arrangements for recycle or fast-breeder systems supporting partial fuel cycles in dispersed locations, the more difficult the implementation of the required systems arrangement. Another arrangement would have spent fuel returned from LWR's to fast-breeders in a few nations with advanced nuclear-power programs in return for guaranteed, long-term supplies of conventional LEU.

The proliferation resistance attributes of thorium-based fuel cycles may be summarized as follows:

- Fresh reactor fuel containing only denatured U-233 and thorium has an isotopic barrier and at this time is considered more proliferation-resistant than fuel containing plutonium, but somewhat less resistant than LEU. Moreover, it is accompanied by a radiation barrier associated with U-232, which may provide deterrence against the subnational threat. The isotopic barrier may decrease in future decades if enrichment capabilities become more widely available.

- Thorium-based fuel cycles requiring reprocessing and recycle have a level of proliferation resistance which is generally similar to that of closed fuel cycles.

- Thorium-based fuel cycles which require high-enriched U-233 or U-235 introduce additional proliferation vulnerabilities associated with the enrichment, storage, transportation, and fabrication of such materials.

- With particular institutional arrangements, such as restricting sensitive portions of the fuel cycle to multinationally controlled centers, the proliferation resistance of thorium-based fuel cycles could be substantially improved.

It has also been suggested that special nuclear materials (SNM) can be "downgraded" to inhibit use in nuclear weapons by enhancing the emission rate of alpha particles, gamma rays, neutrons, or heat. Judgments about the use of SNM must depend on a detailed knowledge of nuclear-weapons design and testing. Although producing such details would conflict with U.S. nonproliferation policies, three conclusions can be drawn:

- U-233 is, in principle, as weapons-usable as U-235 or plutonium.

- Increasing the emission rate of neutrons in U-233, U-235, or Pu would not preclude their use in weapons. This conclusion also applies to the presence of Pu-238.

- The presence of U-232 in U-233 does not provide effective protection against misuse.

Finally, one approach to the problem of abuse of civilian nuclear activities centers on the development of radically different reactor designs. Several speculative advanced reactor concepts (for example, the gaseous-core reactor or the fast mixed-spectrum reactor) which would appear to have nonproliferation advantages have been examined, but none seems to be without proliferation vulnerabilities. Each of these systems requires resolution of significant technical, safety, and economic uncertainties. Such systems cannot be fully developed for many decades; by then, the context for proliferation concerns and the world nuclear-energy regime will have changed. Nevertheless, some of these systems appear to have enough nonproliferation advantages to warrant further investigation, depending on considerations of technical feasibility, economics, and safety. Advanced concepts are assessed in more detail in Volume VIII.

The improvements discussed above, for the near term and for the longer term, can be conveniently summarized into six basic norms for a strengthened international regime designed to minimize the worldwide distribution of weapons-usable materials while taking account of energy security needs:

1. Use of diversion-resistant forms of materials and technologies

2. Avoidance of unnecessary sensitive materials and facilities

3. An effective export control system

4. Joint or international control of the necessary sensitive materials and facilities

5. Full-scope safeguards and a timely international system of warning and response

6. Institutions to ensure the availability of the benefits of nuclear energy.

2. ASSESSMENT OF CIVILIAN NUCLEAR SYSTEMS

Nuclear fuel-cycle systems consist of the particular realizations of nuclear fuel-cycle materials, facilities, and activities in different geographic deployments within different institutional arrangements and controls. These systems are of two basic types: once-through and closed. The once-through system uses fuel in a reactor only once and discharges spent fuel into storage. The closed system returns the discharged spent fuel for reprocessing and refabrication into new fuel elements. These types may be further classified into three generic fuel cycles, which are conveniently designated by the corresponding reactors or processes distinguishing them: once-through (2.1), and recycle (2.2.1) and fast-breeder (2.2.2), respectively.

The two fuel cycles of the closed fuel-cycle system share many features which affect their proliferation resistance. But in other features important to proliferation resistance, they differ markedly. For example, both fuel cycles require reprocessing and fabrication of processed material into fuel elements. However, the potential for near-term deployment of recycle exists because of the widespread deployment of LWR's, while commercialization of fast-breeder reactors is several decades in the future. Moreover, while there are more than 20 countries which have LWR's deployed, only a few countries have significant plans for commercialization of fast breeders, and these plans have much less urgency than in the recent past. This disparity is expected to grow with time. Other differences which affect their proliferation resistance include the content of fissile material in fresh-fuel elements, typically 5% in recycle systems and 15 to 25% in fast-breeder systems.

The discussion of all three generic nuclear-power systems proceeds in the manner earlier described. However, because of the many similarities between the recycle and fast-breeder systems, the reference fuel cycle of the former is discussed at length, of the latter, in brief; unnecessary repetition is avoided, though similarities are noted, and salient differences are appropriately addressed and emphasized.

A discussion of research reactors and critical facilities is provided in Section 2.3. Although the emphasis of Chapter 2 as a whole is on the analysis of individual fuel-cycle alternatives and their comparisons,

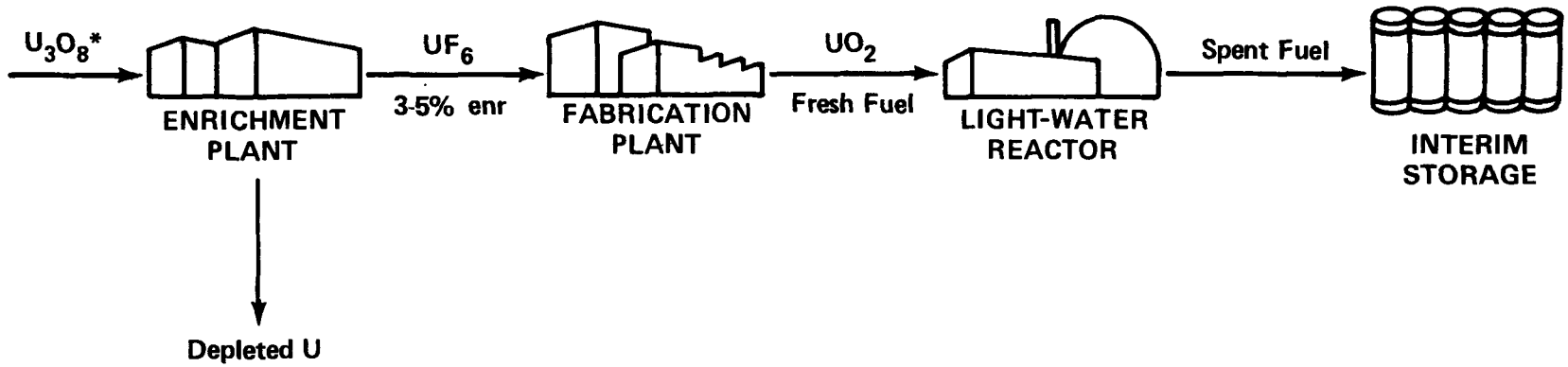
Section 2.4 indicates briefly how these analyses then have to be considered in the context in which systems coexist.

2.1 ONCE-THROUGH FUEL-CYCLE SYSTEMS

2.1.1 Reference Once-Through System with a Light-Water Reactor

A once-through LWR system involves mining and milling uranium ore, enriching uranium to a concentration of about 3 to 5% in the U-235 isotope, fabricating the enriched uranium into reactor fuel elements, using this fuel in the LWR to generate power, and then discharging the fuel into interim storage without deciding whether to put it into either long-term storage or permanent disposal. It should be noted that spent fuel from intermediate storage could later be used in a closed fuel-cycle system (Section 2.2). The reference once-through system is illustrated in Figure 2.1-1.

LWR's fueled with LEU are widely available commercially, generally as boiling-water reactors (BWR's) or as pressurized-water reactors (PWR's). These two types of reactor differ markedly in physical characteristics but do not differ substantially in their proliferation resistance. Currently, there are more than 58 LWR's deployed outside the U.S. in 16 nations. An additional 103 LWR's have been ordered by these and 13 other nations. It is anticipated that by 1986 nearly 90% of all civilian nuclear power in the world outside the centrally-planned economies will be generated by LWR's. It is important to note that enrichment plants are much less widely deployed than reactors are. Currently, only one NNWS, the Netherlands, has a civilian centrifuge enrichment plant deployed, but other centrifuge plants in the Federal Republic of Germany (West Germany) and Japan are planned for in the 1980's. Enrichment facilities will probably become more geographically dispersed than at present, since Brazil and South Africa are also planning for civilian aerodynamic enrichment plants. Moreover, several of these countries already have small-scale or pilot enrichment facilities, and a number of countries apparently are conducting research programs on advanced isotopic separation (AIS) techniques. On the basis of this existing and planned plant capacity and on current demand projections, enrichment capacity outside the centrally-planned economies excluding the United States will begin to exceed aggregate demand in the late 1980's. Including the United States, enrichment capacity is expected to exceed demand at least through the mid-1990's. Against this background of nuclear-power deployment, this section assesses the proliferation resistance



*Product of the mining, milling, and conversion of uranium ore.

Figure 2.1-1. Reference Once-Through System

of the LWR once-through fuel-cycle system within the context of the current institutional regime.

This international regime varies from one country to another. By ratifying the NPT, more than 100 NNWS's have agreed not to acquire or manufacture nuclear-weapons (or explosive) devices and to subject all their peaceful nuclear activities and any nuclear materials or facilities that they export to IAEA safeguards. These nations have thus agreed to what is sometimes called "full-scope" safeguards. These safeguards require that the IAEA independently verify national systems of material control and accounting to maintain continuity of knowledge and inventory of material. Verification is accomplished through a system of reports, physical inspections, independent measurements, and application of various containment and surveillance techniques.

In addition, as a result of various bilateral supply agreements, some non-NPT parties have also agreed to subject specific materials and facilities--but not necessarily all peaceful activities--to IAEA safeguards and not to use those so supplied for weapons purposes. Bilateral and multinational agreements (such as the Nuclear Suppliers Guidelines) may apply to the transfer of nuclear materials or technologies. An example of a bilateral agreement would be one requiring the application of full-scope safeguards as a condition of sale. A notable example of multinational agreements is the supply system and regulatory regime of the European Atomic Energy Community (EURATOM).

Proliferation Features and Activities

The most significant feature of the reference once-through nuclear-power fuel cycle is that directly weapons-usable material is never part of the fuel cycle itself. Fresh fuel contains low concentrations of U-235 (about 3 to 5%) diluted in U-238; spent fuel contains low concentrations of U-235 and plutonium (each less than 1%), both of which are diluted in U-238 and accompanied by high radiation fields emitted by the products of fission. Refueling of LWR's is conducted in a batch mode, with approximately one fifth of the BWR to one third of the PWR reactor core discharged annually.

LEU, as defined by the Nuclear Regulatory Commission (NRC), is uranium enriched to less than 20%; LEU used in LWR's is usually enriched to 3 to 5%. For purposes of this discussion, HEU is defined as uranium enriched to more than 20% and may be weapons-usable. However, in discussions of the production of weapons-usable material, it is conventionally regarded as enriched to 90% or more.

There are three important proliferation pathways by which the reference system may be used to acquire weapons-usable materials: in-system enrichment facilities to produce HEU, out-of-system enrichment facilities to produce HEU, or out-of-system hot-chemical reprocessing (separation) facilities to extract plutonium from the spent fuel. These pathways are examined by noting the activities a potential proliferator would have to undertake and evaluating them when appropriate in terms of the chosen assessment factors. These required activities, including preparation of facilities, removal of material from the fuel cycle, and material conversion, may vary substantially with the scope and kind of the proliferator's nuclear-weapons program. (The word "diversion" is used for removal of materials from the fuel cycle if they are under safeguards.)

In-System Enrichment -- The key proliferation activity in the abuse of an existing enrichment plant designed to produce LEU is the modification of the layout or operation of the plant to permit production of HEU. While several methods of enrichment exist (see Section 3.1), only gaseous-diffusion and gas-centrifuge plants are deployed commercially. Modification of the layout or operation of an enrichment plant depends on the plant type.

In a gaseous-diffusion plant, rearrangement of the cascades designed to produce LEU would not be practicable for continuous production of HEU because of the size of the equipment. Making multiple passes through the cascades, that is, batch-recycle, would yield HEU over many months or even years, but it would require many years' worth of production material in the first cycle to ensure that the cascade is filled in later cycles. Moreover, LEU production would have to cease. Modifying the operating conditions, that is, a "stretched," off-design operation, however, is a more attractive technique for producing HEU. It is the shortest path for producing HEU from a commercial diffusion plant because it uses LEU from the plant inventory for direct enrichment. Weapons-usable material can be produced in a few months after the stretched, off-design mode is initiated. The length of time depends upon the desired degree of enrichment. In a centrifuge plant, rearrangement of the cascades or batch recycle could yield HEU within a matter of weeks if all the

separative capacity of the plant were used. Over a longer period, this HEU could, in principle, be produced with only a modest reduction in declared LEU production.

Out-of-System Enrichment -- The main activity needed to enrich uranium independently of an existing enrichment plant is building and testing an enrichment facility. Competent personnel without specialized enrichment experience would require several years and about a hundred million dollars to build and test a plant capable of producing quantities of HEU for tens of weapons per year. If LEU fresh fuel were removed from the commercial fuel cycle, the time from removal to weapons-usable material would vary from a few weeks to months, depending on the technology used, the capacity of the plant, and start-up difficulties. If this path were chosen, however, a nation might instead choose to enrich natural uranium rather than LEU fuel to reduce the risk of detection.

Out-of-System Reprocessing of Spent Fuel -- The main activity needed to extract plutonium from spent fuel is building and testing a hot-chemical reprocessing plant. Personnel including chemical engineers but without specialized reprocessing experience would require one or two years and tens of millions of dollars to build and test a plant that could separate enough plutonium for tens of weapons per year, somewhat smaller commitments for one or two weapons. Once the plant was built and spent fuel was removed from the commercial fuel cycle, the time from removal to weapons-usable material would vary with competence of the personnel involved. The time could be as short as a few weeks, but it could also be longer if difficulties were encountered in remote reprocessing. (For a discussion of reprocessing methods, see Section 3.3.)

On the basis of the current relative availability of detailed process information and personnel, the isotopic barrier to the production of weapons-usable material from fresh fuel appears greater than the chemical or radiation barrier to the production of weapons-usable material from spent fuel. Several nations have experience with R&D reprocessing facilities in anticipation of recycle or fast-breeder systems, and such a facility could perform the function of the out-of-system reprocessing facility described above. The relative difference between the isotopic barrier and the radiation or chemical barrier could change, if, for example, it became common practice for enrichment facilities to be part of national fuel cycles or enrichment technologies became less difficult. (For a discussion of enrichment technologies, see Section 3.1.)

Figure 2.1-2 illustrates the proliferation pathways of the reference once-through system.

National Contexts

LWR Only -- For a country in which the national fuel cycle included only LWR's with their associated fresh-fuel and interim spent-fuel storage facilities, the significant proliferation activities are building an out-of-system enrichment plant to enrich fresh fuel further or building an out-of-system reprocessing plant to separate plutonium from spent fuel. Building and testing these plants would require the times and resources estimated earlier.

Since construction activities extend throughout a lengthy period of time during which they might be detected by other nations, there may be time for an international response. If full-scope safeguards are applied, these activities would legally have to be declared to the IAEA for design review. If IAEA safeguards were in effect, then the diversion of materials would be subject to IAEA detection. However, once construction were completed, the time from diversion of fresh or spent fuel to significant quantities of weapons-usable material might be as little as a few weeks. Since the time from diversion to detection could be several weeks or even months, timely detection may not always be ensured. The diversion of fresh-fuel, as opposed to spent-fuel, assemblies can represent some additional costs to the proliferator.

For a subnational group, the resources and time to build a clandestine enrichment or reprocessing plant are likely to be very formidable obstacles.

LWR plus Enrichment Plant -- For a country in which the national fuel cycle included not only an LWR and associated fresh- and spent-fuel storage, but also an enrichment plant, there are proliferation pathways in addition to those discussed above. The commitments of time and money required for such misuse would depend on the type of facility. The probability of detection would depend both on the plant type and on international safeguards.

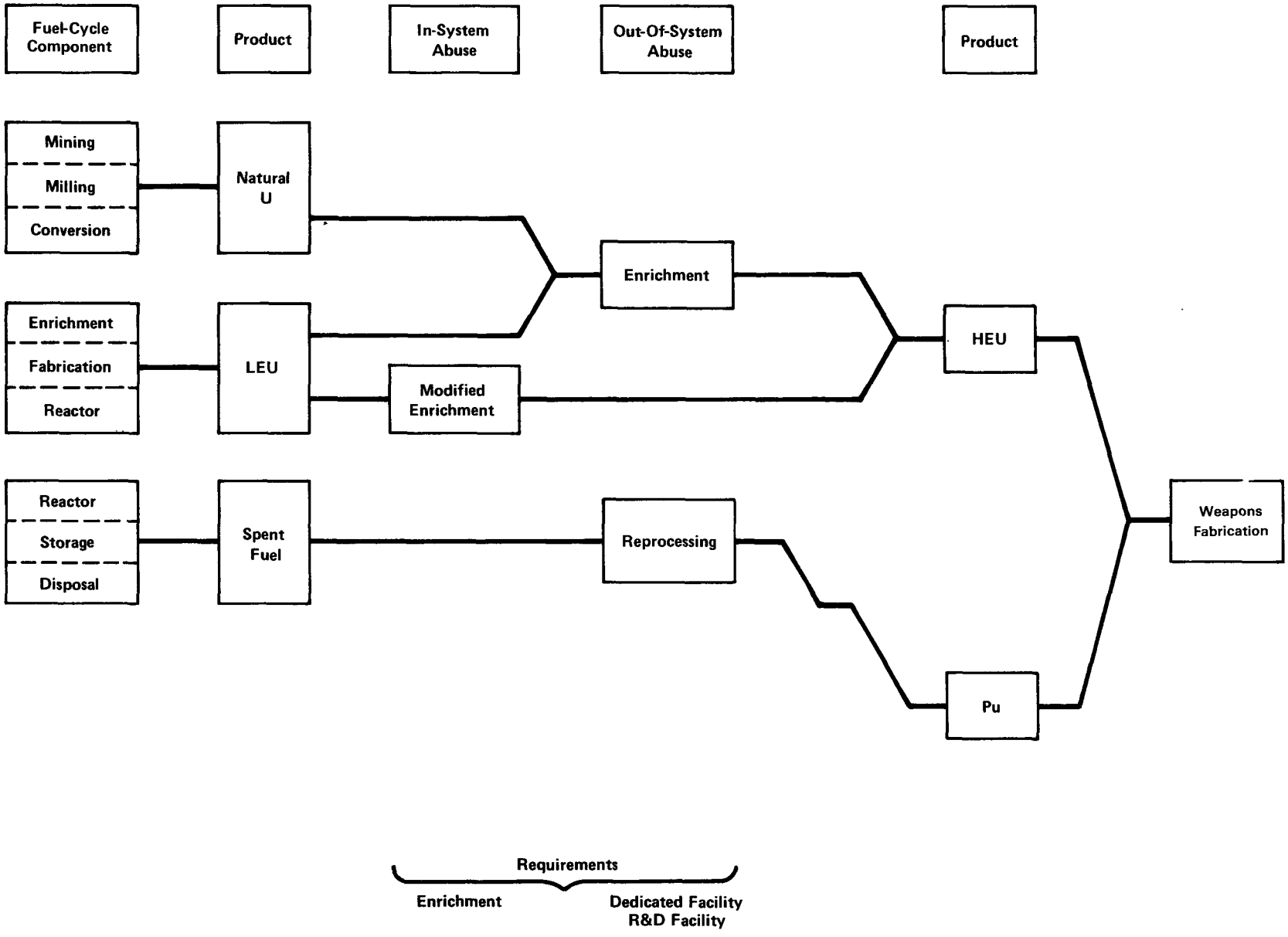


Figure 2.1-2. Proliferation Pathways: Reference Once-Through System

If the enrichment plant were not under IAEA safeguards, then its modification to produce HEU would be difficult to detect. Even if the enrichment plant were under IAEA safeguards, the modification of centrifuge plants to produce a small sidestream of HEU could be more difficult to detect if inspectors did not have access to the plant. However, the safeguards benefits of such access need to be balanced against the risk of sensitive technology transfer. Moreover, the warning time afforded by detection of HEU production in centrifuge plants could be shorter than that of other types of plants.

In addition, the presence of an enrichment plant in a country may provide expertise facilitating the construction and operation of an undeclared, unsafeguarded facility for producing HEU with either unsafeguarded natural uranium or diverted fresh fuel as the feed material.

The subnational threat would be greater than in the LWR-only case, particularly if the enrichment technology involved were susceptible to covert deployment by a group within a government and acting without its approval.

Improvements

The preceding discussion leads to the identification of several measures to maintain or increase the proliferation resistance of the reference once-through system. These measures include improved international safeguards, cooperative arrangements for spent-fuel storage, and cooperative arrangements for the supply of enrichment services.

Improved International Safeguards -- The present international safeguards regime is based on a system of material accounting, containment, and surveillance. These measures apply to any nuclear-power system including the LWR system treated here. Substantial advances in proliferation resistance would be afforded by securing wider acceptance of full-scope safeguards and, in some cases, by strengthening their implementation. Some major improvements of current safeguards for the once-through system might include:

- Improved methods in material accounting, containment, and surveillance to be applied to enrichment facilities and stockpiles

of natural uranium and LEU. Methods which achieve near-real-time, tamper-revealing, remote surveillance of spent fuel in storage are technically feasible.

- o Surveillance of all nuclear material in a country, whether on-site or in transit.

- o Assurance of adequate access to the enrichment plant to achieve effective IAEA plant inspection. The plant should be designed to enable IAEA inspectors to verify that there has been no diversion of materials or misuse of facilities. But procedures would also have to be designed to protect sensitive enrichment technology from being transferred.

- o Improved mechanisms for prompt inspection and swift reporting of possible diversions.

Cooperative Arrangements for Spent-Fuel Storage -- International arrangements for storage of spent fuel, including centralized sites, would assist countries utilizing a once-through cycle by relieving pressure on national storage capacity. Such arrangements, implemented under IAEA safeguards, could have the following nonproliferation benefits:

- o Effective safeguards could more easily be ensured with fewer resources.

- o The impetus for reprocessing could be reduced by providing additional storage capacity.

- o The proliferation risk of leaving spent fuel under national control for long periods, after which the reduced radiation levels could facilitate the separation of plutonium from some spent fuel, would be reduced.

Associated with such cooperative arrangements would be the establishment of fuel-transport links. Since fuel must eventually be transported from reactor sites in any case, cooperative fuel-storage arrangements should be carefully implemented to minimize the proliferation risk associated with transport.

Cooperative Arrangements for Supply of Enrichment Services -- Because the most sensitive portion of the reference system is the enrichment plant, a key

aspect of a continuing nonproliferation regime for this system is reliable access to enrichment services. To reduce the motivation and justification for national plants, it is desirable that existing plants reliably provide services at competitive prices and that new plants be constructed as cooperative ventures under effective international or multinational control as the need for them clearly arises. Financial or other participation in international or multinational enrichment ventures might be one means of providing assurances of a reliable fuel supply while avoiding the heavy financial burden associated with national plants. However, these ventures may involve a risk of diffusing sensitive enrichment technology. Measures are needed to deal with ongoing enrichment R&D and, more particularly, to avoid such activities in the absence of a clearly demonstrated need. Comprehensive participation in an international regime assuring all nations of a reliable fuel supply can be one component in cooperative efforts to reduce the danger of proliferation.

2.1.2 Improved Light-Water Reactors and Other Once-Through Systems

Most of the alternate once-through fuel cycles examined offer the promise of providing increased uranium utilization. From the perspective of proliferation resistance, increased uranium utilization could ease some of the concerns for security of supply and thereby reduce the impetus for reprocessing.

Alterations of LWR systems being considered range from changes in the materials used for the fuel, including thorium, to changes in fuel management and burnup. Improvements in uranium utilization of up to 30% are contemplated, some of which would reduce the need for enrichment services and would result in a reduction of about 25% in the amount of plutonium discharged annually. Changes involving thorium could be significant from the point of view of proliferation because increases in the enrichment level of uranium would be required. On the one hand, the use of 20% enriched uranium would reduce by a factor of from two to ten the separative work required to enrich fresh fuel for use in nuclear weapons. On the other hand, the amount of plutonium in the fuel would be decreased, and the difficulty of extracting it might be somewhat increased. However, as long as the current enrichment supply regime continues, the LWR with improvements would not entail a significantly different proliferation risk from that of the reference system. The safeguards implications of improvements in fuel management which involve disassembly of fuel bundles at the reactor require further evaluation.

Another once-through system that is already commercially deployed is the Canadian Deuterium Uranium (CANDU) heavy-water reactor; however, the number of HWR's deployed is about one tenth that of LWR's deployed. This reactor, which makes more efficient use of uranium than does the LWR, has three features that make it different from LWR's from the perspective of proliferation resistance: it uses natural, rather than low-enriched, uranium for fuel; it uses heavy water as a moderator and coolant; and it uses on-line, rather than batch, refueling.

The CANDU HWR does not require enrichment services and does not encourage reprocessing. Since the use of natural uranium removes the need for enrichment services, widespread deployment of the CANDU HWR fuel cycle would reduce the impetus for the spread of enrichment technology and the attendant risks, but it would also reduce the degree of leverage exercised by the suppliers of enrichment services to effect stringent nonproliferation requirements. And since reprocessing for recycle in HWR's is economically less attractive than in LWR's, this system would also reduce the impetus for reprocessing. Thus, if a nation with a CANDU HWR moved toward acquiring either an enrichment or a reprocessing facility, it would raise justifiable concern that the true objective was material for weapons.

While the CANDU HWR eliminates the need for enrichment services, it creates a need for heavy water. Widespread deployment of the CANDU HWR fuel cycle would create a large annual demand for heavy water to supply initial inventories, approximately 0.85 metric tons per megawatt of installed electric capacity. However, the annual requirement for making up normal losses of a standard 600 MWe CANDU HWR is approximately 0.3%, or 1 to 2 metric tons, of total inventory. Quantities on this scale might be accumulated over a few years by operating a small pilot plant, which, unlike a large production facility, is relatively easy to build and operate. Accordingly, the leverage associated with the need for heavy water in operating HWR's is less than that for uranium enrichment, which is required on a much larger scale.

Heavy water, like graphite, is a material that can be used in production reactors fueled by natural uranium; such reactors are designed to produce plutonium for nuclear weapons. In a country with a commercial HWR fuel cycle including a heavy-water production capability, diversion of enough heavy water to moderate a production or a research reactor (e.g., 17 metric tons, for a typical 30 MWth reactor) may be less visible than the acquisition of the necessary quantity of graphite. Under guidelines agreed upon by the Nuclear Suppliers, the export of heavy water and heavy-water technology triggers the

application of safeguards. However, there is no present consensus on further conditions to limit the transfer of this technology. Although the use of natural uranium results in more plutonium production in a CANDU HWR than in the reference LWR (500 kg versus 250 kg per gigawatt-year of operation), the concentration of plutonium per kilogram of fuel is lower. Consequently, since it would require two-and-a-half times more spent fuel from a CANDU HWR than from an LWR (30 versus 12 metric tons) to obtain 100 kg of plutonium, the time required to extract it would be somewhat greater.

Unless special safeguard measures are applied, the use of on-line refueling makes the CANDU HWR fuel cycle more susceptible than the reference LWR to covert diversion. With the excess capacity of the on-line fueling machines and additional quantities of undeclared fresh fuel, this fuel may be irradiated to less than normal burnup and thereby increase the weapons quality of the plutonium produced. Over the past three years, Atomic Energy of Canada, Limited (AECL) has, in cooperation with IAEA, devised a safeguards system to detect abuse of on-line refueling. The system incorporates means for counting the short (0.5m) fuel bundles discharged from the HWR and for verifying that the bundles in the spent-fuel pool are not dummies substituted for irradiated fuel. Surveillance and containment security are provided by cameras and radiation monitors. Although the conceptual design seems sound and prototype equipment has been operating satisfactorily at the Pickering Center in Canada for several years, an informed judgment on the efficacy of the complete system awaits its installation on a reactor in early 1980 and the accumulation of significant operating experience.

On balance, a comparison of the proliferation resistance of the reference LWR and the CANDU HWR presents mixed results. Although a heavy-water production capability does not provide so direct a route to a nuclear-weapons capability as does either uranium enrichment or spent-fuel reprocessing, caution should be exercised in the transfer of this technology. Special safeguards for on-line refueling are also needed. An HWR fuel cycle may also serve as a civilian starting point for a nuclear-weapons program. As such, its advantages to the potential proliferator are that it shortens lead times while maintaining ambiguity of purpose, advantages cited in 1970 by the Indian strategic analyst K. Subramanyan.

Another natural-uranium HWR besides the CANDU which utilizes on-line fueling has been commercialized in Argentina. The 320 MWe reactor is of pressure-vessel, rather than pressure-tube, design, and the fuel is contained in long (5.0m) rods rather than short bundles. The fueling pattern requires

replacement of one bundle per day or 30 per month; by comparison, the pattern for a 600 MWe CANDU HWR requires replacement of about 250 bundles per month. The smaller number of large fuel elements should make covert diversion more difficult, but in other respects, this HWR has proliferation risks similar to those of the CANDU HWR.

Some modifications in the fuel for standard CANDU HWR's may marginally improve its proliferation resistance. The use of uranium fuel enriched to 1.2% would improve uranium utilization substantially by reducing uranium requirements about 25% below requirements for the standard CANDU HWR using natural uranium. It would reduce the amount of plutonium in the spent fuel in HWR's to about the level in current LWR's and would reduce the amount of spent fuel generated from five times (HWR with natural uranium) to two times (HWR with 1.2% enriched uranium) that of an LWR. But while the use of such fuel would reintroduce a dependence on enrichment services, it could also provide a pretext for developing an independent enrichment capability.

The use of 20% enriched uranium/thorium fuel in the HWR would lower the isotopic barrier at the front end of the fuel cycle but would substantially increase the difficulty of misusing spent fuel. That is, about one tenth the number of centrifuges would be needed to produce a given amount of HEU than would be needed if one began with natural uranium. However, approximately 12,000 spent-fuel elements, or about 4 to 5 years of reactor discharge, would be required to accumulate 100 kg of plutonium from an HWR operating on such fuel, whereas about 28 fuel elements (about 60 are discharged for each gigawatt-year of operation) are required to recover the same amount from an LWR. This requirement would represent a significant and potentially detectable logistics problem for the potential proliferator. On the other hand, large quantities of chemically separable U-233 denatured with U-238 would also be discharged in the spent fuel. The U-233 would be accompanied by radiation from U-232 and the products of its decay, an industrial disadvantage but a minor proliferation resistance advantage. The separative work required to enrich the U-233 and U-235 in the spent fuel would be comparable to that in the fresh fuel, but the spent fuel would first have to be separated in a hot-processing facility. These modifications could mitigate the proliferation vulnerabilities of the HWR by reducing plutonium production and thereby improving the ability to safeguard spent fuel. These improvements could narrow the difference in comparison with the LWR, but the use of 20% enriched uranium would mean that the separative work needed to misuse the uranium either in fresh fuel or spent fuel would be about five times less than for conventional LWR fuel. Moreover, there would remain the disadvantage of introducing heavy water and enhancing the capability to pursue the independent path.

High-temperature gas-cooled reactor (HTGR) fuel-cycle concepts, which appear to have potentially significant proliferation resistance features for once-through cycles, have been proposed. The high-temperature gas-cooled reactor designed in the U.S. and the high-temperature pebble-bed designs being developed in West Germany, for example, appear to permit low-enriched fresh fuel (less than 20% U-235), and very high burnup. In HTGR fuel cycles that use LEU and no thorium, fissile plutonium discharged annually would be about one third that of a comparably sized LWR. In HTGR uranium/thorium cycles, fissile plutonium discharge would be about one tenth of that of a comparably sized LWR. The need to divert increased amounts of spent fuel would present an increased logistics problem for the potential proliferator. Moreover, processing HTGR fuel is somewhat more complex at the front end of the process. On the other hand, the amount of separative work required to enrich the fresh fuel to about 90% U-235 would be one tenth that for natural uranium. U-233 would be produced in the spent fuel, but the fuel cycle could be designed so that the U-233 would always be mixed with a sufficient quantity of U-238 to keep the mixture below weapons-usable levels. Unless the HTGR is fueled with LEU, the proliferation resistance of the front end of the HTGR fuel cycle is significantly less than that of the LWR system. Accordingly, it does not appear that the nonproliferation advantages are sufficient to prefer this fuel cycle to the LWR cycle.

There are also other types of gas-cooled reactors (e.g., MAGNOX) fueled with natural uranium and commercially deployed in a number of countries, particularly Britain and France; these reactors have plutonium production comparable to an HWR. The spectral-shift-controlled reactor (SSCR) has the potential for slightly improved resource utilization over conventional LWR's operating on a once-through fuel cycle, but it requires heavy water. However, there are no significant differences between the proliferation resistance of the LWR and SSCR once-through fuel cycles.

2.1.3 Summary of the Proliferation-Resistance Assessment of Once-Through Systems

The LWR using fuel once and discharging the spent fuel to interim storage serves as a reference for the generic class of once-through systems. Regardless of the important pathways for abusing this cycle, materials used in once-through systems are never directly weapons-usable, and out-of-system facilities must be prepared before the materials can be converted to weapons-usable form, including facilities for separating plutonium, which would not otherwise be deployed. One of the greatest proliferation risks would arise

if the potential proliferator had an enrichment plant. For example, all the activities to obtain weapons-usable HEU from an operating centrifuge plant could take as little as a few weeks and could be very difficult to detect. In the near term, few countries are expected to have enrichment plants as part of their nuclear-power systems, but there is a trend toward the acquisition of this technology by nations with advanced nuclear-power programs.

In the absence of an existing enrichment plant, a facility to obtain weapons-usable HEU from fresh fuel would require considerable technical expertise, substantial financial commitments, and a period of many years. But, in this context, spent fuel would represent a greater proliferation risk, particularly in the absence of adequate safeguards, although the facility needed to extract weapons-usable material could take a year or two to build. Once operational, however, such a facility could produce weapons-usable material from spent fuel within weeks of removal. Moreover, as more spent fuel accumulates, the impetus for reprocessing will grow either for waste management or in anticipation of recycle or fast-breeder systems.

On balance, the once-through cycle, in which spent fuel is discharged to storage, is found to possess relatively high barriers to proliferation at this time. The vulnerabilities examined and the evolving situation, however, point to the need for improvements to maintain the proliferation resistance of this cycle. These improvements and the desired effects they would be designed to achieve can be summarized as follows.

Stringent safeguards on spent fuel in storage and in transit, combined with storage under international auspices, could significantly reduce the covert proliferation potential of this material by making its diversion more detectable. A storage system under international or multinational auspices would also reduce the impetus for reprocessing as a way to alleviate the pressures of increasing accumulations of spent fuel. Applying safeguards to enrichment facilities would also make their misuse more detectable. Limiting the number of such facilities and emphasizing cooperative arrangements with restrictions on technology transfer could help maintain the current level of proliferation resistance associated with the reference once-through system. Additionally, restraints on sensitive technologies, coupled with reliable access to enrichment services, would make the preparation phase of a nuclear-weapons program more difficult and time-consuming, and could make the identification of such preparations less ambiguous.

Another once-through system that is now commercially deployed, unlike the alternative once-through systems mentioned below, is the CANDU HWR. From the point of view of proliferation resistance, this system is distinguished from the LWR by three technical features: the use of natural uranium, heavy water, and on-line refueling. The use of natural uranium removes the need for enrichment facilities, with their associated risks. But the availability of heavy water can complete a nuclear-weapons material production capability if unsafeguarded natural uranium and out-of-system spent-fuel reprocessing facilities are also available. Other disadvantages would include the production of more plutonium, even though in more dilute form, and as-yet-unproven and, in any case, more complex safeguards for heavy-water and on-line refueling. Several suggested modifications would mitigate some of these disadvantages.

For once-through systems, various alternatives are currently under consideration. Most of these offer the promise of uranium utilization, easing some concerns for security of supply, and reducing the impetus for reprocessing. While improvements in uranium utilization in LWR's would not significantly affect their proliferation resistance, such improvements reduce the fissile value of spent fuel and thereby indirectly improve proliferation resistance. One alternative, the SSCR, would also have the increased proliferation risk of introducing heavy water to the nuclear-power system. The use of a fuel cycle using 20% enriched uranium and the introduction of thorium have been considered for LWR's, HWR's, and HTR's. This would reduce by about five times the separative work required to enrich fresh fuel for use in nuclear weapons. There would also be large amounts of similar material in the spent fuel, including U-233 of equivalent enrichment. On the other hand, the amount of plutonium in the fuel would be decreased, and the difficulty of extracting it would probably be increased. The use of HEU feed in any of these reactor types would, of course, greatly decrease the proliferation resistance of the once-through cycle.

Because of the present deployment and commitment to conventional LWR's, the development time required for introducing new fuel types, and the nature of the differences in proliferation resistance discussed above, it appears that there are no nonproliferation reasons for preferring or not preferring any of the alternatives to the LWR once-through fuel cycle with interim storage of spent fuel.

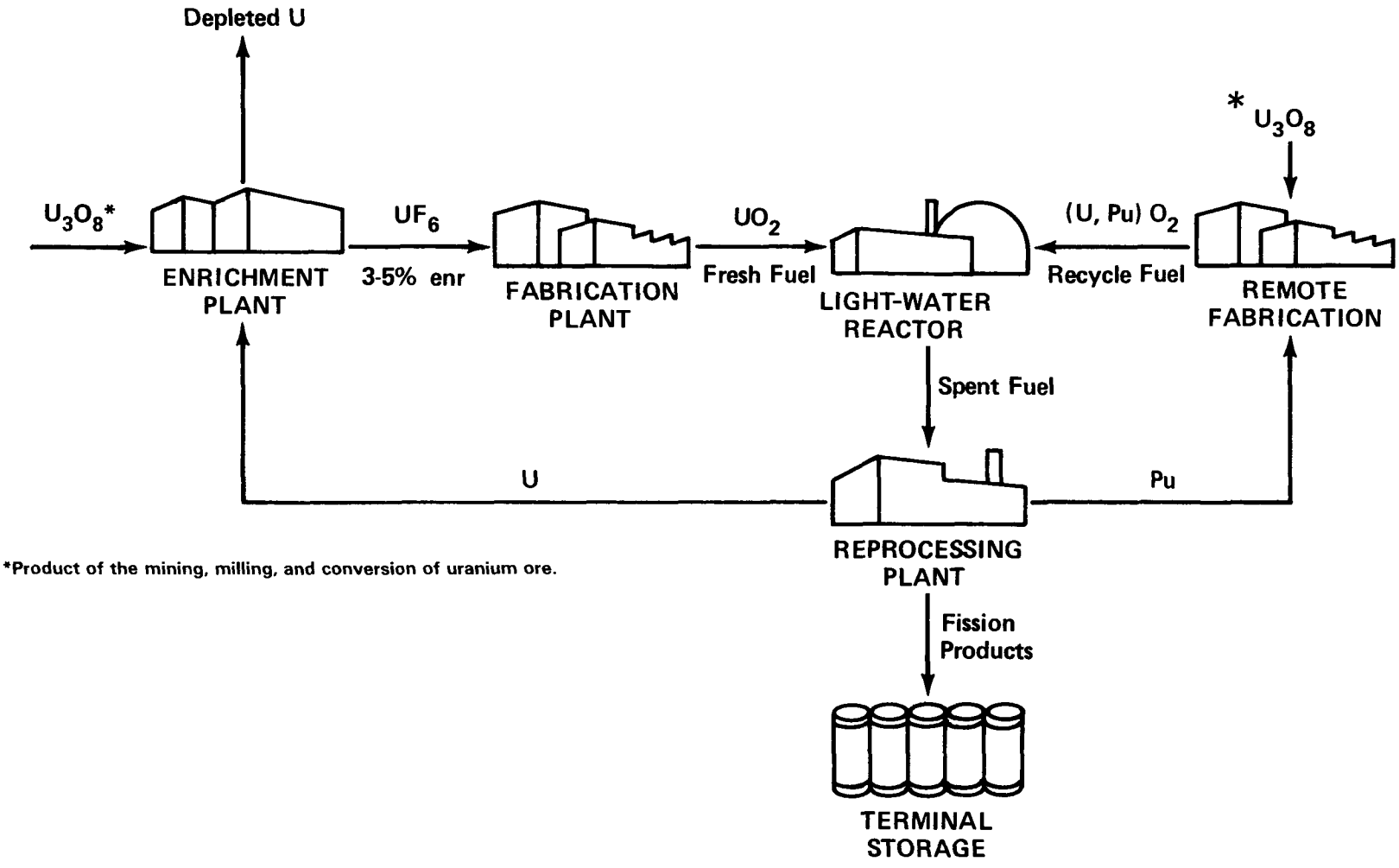
2.2 CLOSED FUEL-CYCLE SYSTEMS

2.2.1 Reference Recycle System with a Light-Water Reactor

To the facilities used and operations conducted in the reference once-through system, the reference uranium-plutonium recycle system adds reprocessing and fabrication plants, which handle separated plutonium and fresh MOX fuel. The reference recycle system uses the fissile material generated in spent fuel by separating it and burning it in LWR's. The reference system consists of the currently conceived, PUREX-based reprocessing method and MOX fuel refabrication within the context of the current institutional regime. The reference recycle system is illustrated in Figure 2.2-1.

More than ten NNWS's have operated some type of spent-fuel reprocessing facility, at least on a laboratory scale. Although some of these facilities have been shut down and in some cases dismantled, the ability to separate plutonium from spent fuel is not uncommon in the world. And by 2000, Belgium, Brazil, Britain, France, India, Italy, and Japan plan to have commercial facilities for processing oxide fuel from LWR's. The commercial facility planned by West Germany was recently deferred. Outside the centrally-planned economies, Argentina is the only other country with announced plans for commercial reprocessing before 2000. By about 1985, Spain plans to make a decision on commercial reprocessing. With the possible exception of Brazil, all countries with announced plans for commercial reprocessing facilities before 2000 have already operated either laboratory or pilot-scale reprocessing facilities.

Of the 660 GWe nuclear-power generating capacity projected by 2000 for the world outside the centrally-planned economies, excluding the United States, approximately 90% will probably be supplied by LWR's. These reactors can operate on MOX fuel. However, plans are indefinite for recycle in most of the countries which plan to have LWR's. Nonetheless, substantial MOX fuel testing and research activities are under way in several countries, among them, Belgium, Italy, and Switzerland. Belgium, Italy, Japan, Switzerland, and West Germany have indicated intentions to preserve the option of recycle in thermal reactors. Japan has an advanced reactor operating on plutonium fuel now and had intended to realize the initial commercialization of plutonium recycle in their LWR's by the mid or late 1980's. This emerging picture of possible imminent deployment of recycle in some nations with advanced nuclear-power



*Product of the mining, milling, and conversion of uranium ore.

Figure 2.2-1. Reference Recycle System

programs is the basis for assessing the proliferation resistance of the reference recycle system.

The technical base for fueling LWR's with MOX is well advanced, although no fully commercialized systems exist. Evaluation of proliferation resistance must not only treat a mature recycle system, but also consider the pilot-scale or prototype full-scale facilities important for training personnel and attaining reliable commercial-scale practice. As discussed above, such facilities already exist or are under consideration in at least 12 countries. Although the existing developmental facilities are under national control, there is a significant variation in the institutional context for such programs. Some, for example, are not subject to IAEA safeguards. However, as these development programs evolve, the institutional regime is likely to evolve also.

Proliferation Features and Activities

The most significant proliferation feature of the reference recycle fuel cycle is that directly weapons-usable material is often part of the fuel cycle itself. Separated plutonium may be present in storage and in transport in forms which may be weapons-usable. Fresh MOX fuel itself can be converted to weapons-usable material through chemical processes which require special handling, but not the shielding needed for spent-fuel reprocessing. Fuel elements typically have 3 to 6% concentrations of PuO_2, and much higher concentrations may be typical in feedstocks. Spent fuel also has plutonium concentrations of several percent but is accompanied by high radiation fields. Thus, in addition to those proliferation pathways shared with the reference LWR once-through system, the reference recycle system has several proliferation pathways of its own.

Plutonium in various forms can be removed from the fuel cycle either in fresh or spent fuel or as separated plutonium in nitrate solution [$Pu(NO_3)_4$] or oxide form (including MOX feedstocks). Fresh fuel would be available at refabrication plants and at reactors. Spent fuel would be available at reactors and at reprocessing plants. Separated plutonium would be available at reprocessing and refabrication plants. If the material removed were spent fuel, hot reprocessing, an integral part of a recycle system, would be required. Most pathways to weapons-usable material would require less extensive preparations and less difficult conversions, such as chemical separation

of plutonium from uranium in the absence of high-radiation fields, than are required from spent fuel. Although the preparations and difficulties are smaller, the actual time to process material to weapons-usable form would be about a week or so, not much different from that for spent fuel.

Out-of-System Conversion of Already-Separated Plutonium -- To convert PuO_2 or $Pu(NO_3)_4$ to plutonium metal requires out-of-system facilities. (Conversion to metal is not now in-system to any civilian nuclear-power system; however, it is involved in certain civilian R&D activities.) Converting already separated plutonium in bulk storage or transport to weapons-usable form does not involve unusual procedures and would not present significant difficulties to most nations with trained or experienced personnel. Under these circumstances, preparation activities for tens of metal weapons per year could be completed within a few months at a cost of a few million dollars and could be difficult to detect. Fewer resources would be required if only one or two weapons were required or if oxides were used directly. The period from the time material was first removed from the fuel cycle until significant quantities of weapons-usable material were produced could be a matter of a few days or weeks. A subnational group would find converting $Pu(NO_3)_4$ to metal a more difficult and time-consuming job than converting it to solid oxide.

Out-of-System Conversion of MOX Feedstocks or Fuel Assemblies -- Out-of-system facilities are also required to convert MOX feedstocks, that is, powder or pellets, to plutonium metal. (Again, conversion to metal is not now an in-system activity for any civilian nuclear-power system.) MOX powder mixed at the fabrication plant from pure PuO_2 and UO_2 would normally contain about 5% PuO_2 for recycle fuels. If these oxides were mixed at the reprocessing plant instead of at the fabrication plant, then feedstock to the head end of the MOX fuel-fabrication plant could range up to 10 or 15% PuO_2. The steps necessary to separate plutonium from uranium are not formidable. After the acquisition of appropriate facilities, which would require up to twice as long as for bulk PuO_2 and a few million dollars to design, construct, and test, material for tens of weapons per year could be separated in a few months. However, significant quantities of weapons-usable material could be produced in approximately one week.

The proliferation activities required to obtain weapons-usable plutonium from fabricated MOX fuel assemblies would be essentially the same, with the addition of a simple sawing operation.

Out-of-System Reprocessing of Spent Fuel -- The main activities would be the design, construction, and testing of an out-of-system plant capable of hot reprocessing. These activities would require competent personnel one to two years and a few tens of millions of dollars for a program to build tens of metal weapons per year. The time between removal of spent fuel from the fuel cycle until significant quantities of weapons-usable material are produced can be a matter of a few weeks. Although the handling of radioactive spent fuel is inherently more difficult than that of the fresh fuel or feedstock material discussed above, especially for subnational groups, it is within the means of many nations.

Figure 2.2-2 illustrates the proliferation pathways of the reference recycle system.

National Contexts

The assessment of the proliferation resistance of the reference recycle system is sensitive to variations in the aspirations to acquire a nuclear-weapons capability. For example, a subnational group may seek only one or two "crude" weapons from plutonium oxide. Alternatively, a nation may seek only a few such "crude" weapons as a prelude to a larger, more militarily flexible program requiring substantially greater resources, including oxide-to-metal conversion capabilities. Accordingly, since there is so wide a variation in potential proliferation situations, the discussion below focuses only on the relevant generic features.

Recycle LWR Only -- For a country in which the national fuel cycle includes only LWR's using MOX fuels and their associated fresh-fuel and interim spent-fuel storage facilities, the significant nuclear-power proliferation pathways (in addition to those involving enrichment) are to build an out-of-system facility to extract plutonium from fresh-fuel assemblies or to build an out-of-system reprocessing plant to process LWR spent fuel. Technically, the preparations for and the conversion of fresh fuel to weapons-usable material is easier than hot reprocessing.

If IAEA safeguards were in effect, the diversion of fuel assemblies would be subject to detection. However, although item counting could greatly

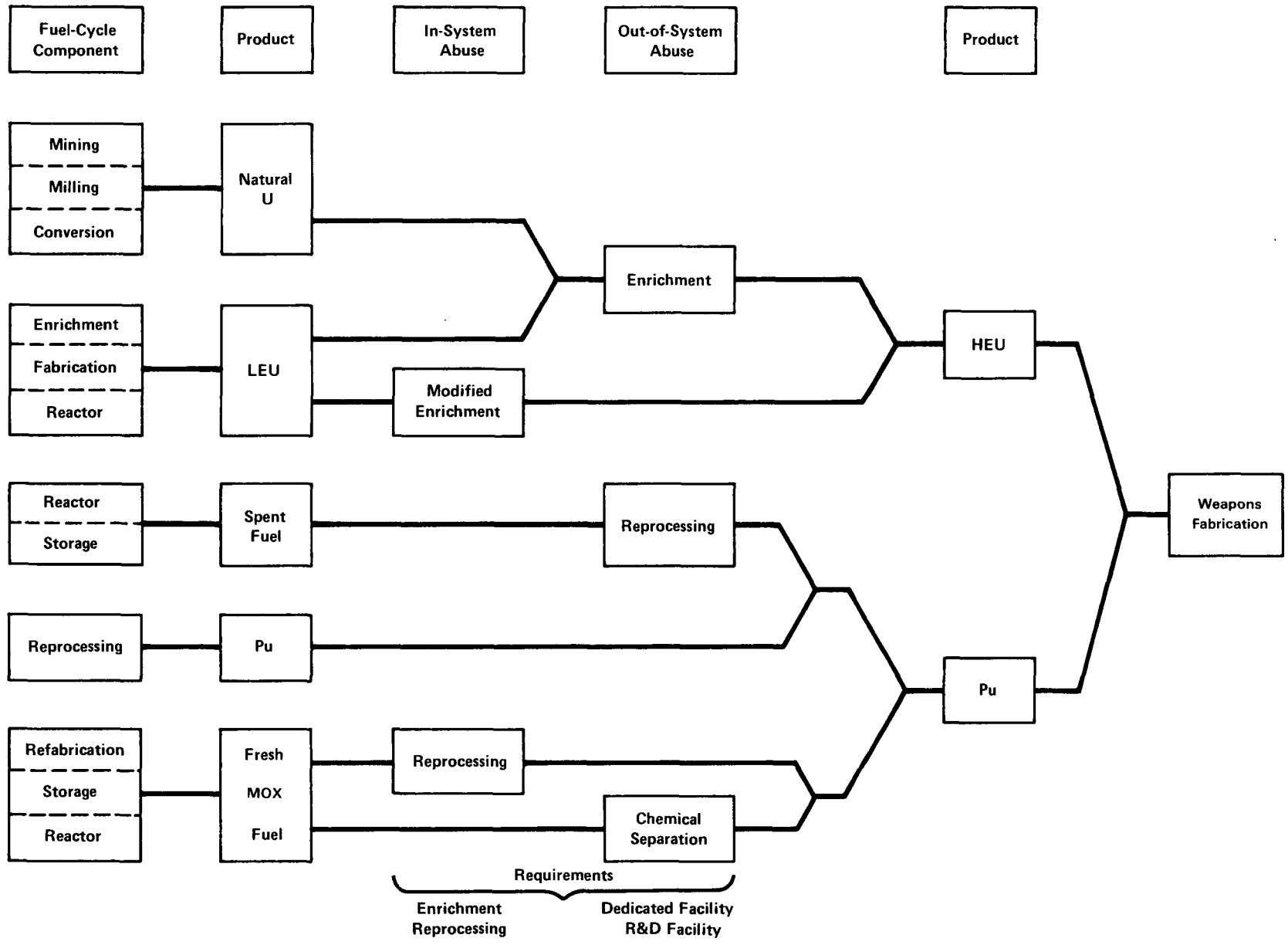


Figure 2.2-2. Proliferation Pathways: Reference Recycle and Fast-Breeder Systems

facilitate detection because of the discrete nature of fuel assemblies, the timeliness of detection and response would be difficult to ensure with today's system since conversion times can be short. If IAEA safeguards were not in effect, the possibility of detection would be quite limited. Subnational groups would have a potentially viable proliferation path through the seizure of fresh recycle fuel. Effective safeguards and physical security would be essential to prevent both covert diversion and overt seizure of materials.

Complete Recycle Fuel Cycle -- For a country in which the national fuel cycle includes reprocessing and refabrication facilities in addition to the LWR, all of the proliferation activities discussed earlier in addition to those of the LWR once-through system are possible.

For NPT parties, IAEA safeguards would apply throughout the recycle LWR fuel-cycle system. However, since the time from diversion to sufficient weapons-usable material may be only days to weeks, ensuring timely detection would be difficult. Because of the presence of plutonium inventories, often in bulk form, and the large flow of plutonium through reprocessing and fabrication facilities, the detection of the diversion of a relatively small sidestream over long periods of time would also be difficult to detect. Without IAEA safeguards, the possibility of detection of diversion would be extremely limited.

A possible proliferation pathway for subnational groups would be the seizure of separated plutonium in bulk form. Effective safeguards and physical security would be essential to prevent both covert diversion and overt seizure of materials.

Improvements

Technical, safeguards, and institutional measures to reduce the vulnerabilities of the reference recycle system may take several closely related forms. A number of modifications have been suggested to make the materials used in the fuel cycle more difficult to convert to weapons-usable materials. More comprehensive safeguards and physical security measures may be introduced to improve the detectability of diversion, as well as to decrease potential access by subnational groups. Particularly sensitive activities in the fuel

cycle, like the processing of plutonium-bearing materials, may be deployed under improved safeguards, or international or multinational control.

A broad array of such technical and institutional measures could be applied to all fuel-cycle systems. The remainder of this section emphasizes those measures that may apply to both recycle and fast-breeder fuel cycles. Differences that apply to the breeder fuel cycles alone are discussed in Section 2.2.4.

Although most of these measures are related to one another, they are placed into three categories for convenience: technical measures, safeguards and physical security, and other institutional measures to provide cooperative arrangements for fuel-cycle services and other fuel-cycle management options.

Technical Measures -- The basic fissile fuel material for the recycle reactor is plutonium. Isotopic dilution cannot render this material unusable for weapons in the way that diluting U-233 or U-235 with U-238 does in once-through systems. Heat spiking of plutonium with Pu-238 would pose an isotopic barrier to its separation. Separation would not be necessary, however, since the heating problem can be easily overcome. Consequently, technical nonproliferation measures for plutonium center on chemical dilution and the provision of a radioactive barrier by radioactive contamination.

Radioactive contamination may be effected either by adding radioactive materials such as cobalt-60 (Co-60) to the plutonium after reprocessing (spiking) or by permitting a portion of the fission products from the spent fuel to remain with the plutonium during reprocessing (partial decontamination). Alternatively, the fuel may be irradiated before leaving the reprocessing/fabrication complex (pre-irradiation). The purpose of such process alterations would be to afford a protective radiation barrier to plutonium-bearing materials, including the fresh fuel. The radiation fields can be substantial and, although not as high as those from spent fuel, can require special handling and remote hot-chemical reprocessing to recover weapons-usable material. Radiation levels on the order of tens to a hundred rem/hr at 1 meter have been judged sufficient to force a nation seeking to produce tens of weapons to conduct reprocessing in a hot facility. This protection would correspond to that of spent fuel 100 to 150 years after discharge from a reactor.

Dilution with uranium may be effected by coprocessing, that is, by managing the plutonium extraction system in a reprocessing plant so that the product from the plant is a mixture of uranium and plutonium rather than just plutonium, or by co-conversion, that is, by mixing extracted uranium and plutonium nitrates at the output of a reprocessing plant. Such approaches significantly increase the amount of material that has to be removed from the fuel cycle and requires the chemical separation of plutonium from uranium.

Other technical measures that have been suggested are much more conceptual in nature and include providing passive engineered features to reduce accessibility to sensitive materials (e.g., PIPEX), adding active denial features to deny use of sensitive facilities and materials, and perhaps providing for integral separation and fabrication (in a manner like that of the CIVEX concept suggested for fast-breeder cycles).

As a means of increasing resistance to national proliferation, the retention of a chemical dilution barrier by coprocessing or co-conversion is not relevant in contexts where only recycle reactors (and not reprocessing and fabrication facilities) are deployed in a given country because the recycle fuel is MOX in any case. In countries where reprocessing or fabrication facilities are deployed, the effect on proliferation resistance of coprocessing would be limited for two reasons. First, separated PuO_2 could probably be readily obtained by simple changes in process control variables or by batch recycle of normal product material. Second, out-of-system facilities for separating PuO_2 from MOX and converting it to plutonium metal would require somewhat more time and resources for design, construction, testing, and operation than those for converting PuO_2. However, the direct use of oxides might be considered under certain circumstances. But an arrangement to minimize or avoid the use of separated plutonium anywhere in the cycle could provide clear evidence of a violation should separated plutonium be found by the safeguards system.

Since MOX intended for use in thermal (or slow-neutron, as opposed to fast-neutron, or breeder) reactors cannot be used directly in a nuclear device, coprocessing would present a substantial barrier to subnational groups throughout the fuel cycle.

The addition or retention of a radiation barrier in recycle materials offers somewhat greater potential for increasing proliferation resistance than

does coprocessing of uranium and plutonium, particularly in countries where no recycle facilities are deployed. This potential is primarily associated with the fact that more elaborate out-of-system facilities would be required to recover plutonium from diverted materials. Such facilities would have to provide for shielding and remote operation, and would take up to perhaps three to five months longer for design, construction, and testing than would facilities processing nonradioactive materials. These additional resources would enhance the opportunities for detection and the potential warning time before removal of materials. The actual operating time for recovery of a given quantity of fissile materials would likely be only slightly longer than with nonradioactive materials.

In realizations in which all fuel-cycle facilities are deployed, the radiation-barrier concept suffers, although perhaps to a lesser degree, from the same weakness as coprocessing, namely, that clean, separated plutonium compounds can readily be obtained by changing process variables or by batch recycle. These changes would eliminate or substantially reduce the requirements for out-of-system facilities. Thus, the radiation barrier would provide only marginal improvements to the system, particularly in the event of an overt national proliferation attempt. Moreover, although radiation might facilitate containment and surveillance, it would be highly detrimental to material accounting as a protection against covert diversion. In fact, most of the nondestructive assay (NDA) methods and procedures which have been or are being developed through years of intensive R&D would be rendered ineffective. But the radiation barrier would represent a substantial impediment to a subnational threat, although its appropriateness in this context will depend on environmental, economic, and safeguards disadvantages.

Clearly, the radiation barrier would offer its greatest benefit in those contexts where only reactors would be deployed in NNWS's. The out-of-system facilities required would be comparable to those required with spent fuel as the starting material.

The introduction of radiation barriers would entail significant economic costs and large but uncertain risks to the public and operating staff. These costs and risks must be considered in evaluating the nonproliferation benefits of radiation barriers and the economics of recycle under these conditions.

It is conceivable that reprocessing and fabrication plants could be combined into an integral facility and designed with engineering features that would make access to plutonium and process modification very difficult or perhaps highly visible to safeguards inspectors. The potential effectiveness of such features is highly dependent upon specific plant design details, however, and cannot be evaluated at a conceptual level. An integrated reprocessing and fabrication facility would eliminate a transportation link and possibly improve prospects for effective safeguards against covert diversion (or overt diversion in the case of subnational threats).

An additional variation of this concept that has been suggested would be to incorporate a combined coprocessing and partial decontamination process so that highly radioactive material throughout the plant would further increase the resistance to covert diversion and theft. The practicality and effectiveness of designing and operating such a plant to prevent abuse by the operators has not been resolved. The difficulties of implementing effective safeguards in such a plant have already been referred to. The additional costs to normal operation would also have to be considered.

A radically different, but possibly supplemental, approach to improving the proliferation resistance of plutonium-based systems is based on the concept of "use denial" by means of active operational features incorporated into fuel-cycle facilities and transport vehicles. In this concept, detection of improper conditions or operations by remote monitoring would lead to automatic shutdown or disruption of operations, to denial of access to certain areas, or to modification of the form of certain materials. This concept would have obvious advantages in protecting against seizure by subnational groups. It has equally obvious problems from the viewpoint of acceptability to facility operators and would offer little protection against overt takeover by the operators themselves, although it might provide some deterrence if combined with effective international sanctions.

None of these facility or process engineering schemes (see Section 3.3 for further discussion of other reprocessing technologies) would, however, appear to mitigate the concern that a national operator might take over the facility and within a very short time have weapons-usable material available. Moreover, operating experience in a plant incorporating any of these concepts would also give the operators effective grounding in at least some of the technology required to build independently a reprocessing facility dedicated to making weapons. This problem, of course, would also extend to multinational operation of reprocessing facilities discussed below.

Safeguards and Physical Security -- The improvements in safeguards and physical security measures that were delineated for the once-through systems are also necessary for recycle systems. The effectiveness of these techniques is especially important for fresh recycle fuel because less extensive preparations and conversion facilities are required to extract plutonium from this fuel. Effective real-time monitoring of both fresh and spent fuel can be developed from technology which has been shown to be feasible. Such monitoring can be aided by careful management to limit the quantity and duration of stockpiles of such materials.

Detecting diversions from recycle facilities would be relatively difficult because plutonium-bearing materials are present in bulk forms. Two difficulties are inherent: developing and implementing effective techniques for detecting long-term diversion of small amounts of material, and meeting goals for timely detection of abrupt diversion of larger amounts.

Safeguards on reprocessing plants cannot be based solely on traditional material accounting methods because measurement errors and uncertainties in the material balance would be too great. Existing safeguards not only would have to be improved, but also would have to be supplemented by an increased emphasis on containment, complemented by human and instrumental surveillance and monitoring. The description of a feasible system along these lines has not yet been provided. But it is thought that IAEA objectives could be met by conducting essentially continuous inventories as well as the usual periodic complete cleanout inventories; upgrading process control information and making it available to inspectors on an essentially continuous basis; demonstrating safeguards technology improvements, such as those developed in the U.S., for use in an international context; strengthening programs for safeguards technology improvements, especially NDA methods intended for on-line or at-line use; improving analytical methods and laboratory facilities, including establishment of inspector-operated on-site laboratories; and including IAEA safeguards objectives as criteria in the design and construction of plants and facilities. Such measures might result in adequate safeguards for large reprocessing plants and thus meet IAEA goals of sensitivity and timeliness. However, it appears that implementing such safeguards will be expensive for the IAEA and the operator, and that their implementation will require a politically significant degree of intrusiveness into plant operations. In addition, technical uncertainties will remain until a large-scale demonstration has been carried through.

To prevent subnational diversion, adequate physical security measures would be required. Some of the measures discussed in the previous section, for example, the introduction of a radiation barrier or coprocessing, and measures discussed in the next section, such as colocation, serve to reduce effectively the opportunity or ease of subnational seizure by providing a radiation barrier for fresh fuel and by reducing vulnerable transportation links in the fuel cycle. The technical measures discussed above may make it easier to safeguard reprocessing plants, but the costs and benefits have not been fully evaluated. One conflict is that the radiation from spiking or similar measures may render inoperative certain NDA assay instrumentation for accounting while improving the effectiveness of some surveillance and monitoring instrumentation. The conflicts which are inherent in the technical improvements must be considered when devising an institutional regime to provide adequate protection against misuse of fuel-cycle materials.

Cooperative Arrangements for Fuel-Cycle Services and Other Fuel-Cycle Management Options -- An important possibility for improving the proliferation resistance of recycle fuel cycles is to put sensitive materials and facilities under international control and to limit the number of such facilities. Bringing such facilities under international auspices would raise additional political obstacles to abrogating safeguards. Some believe that the existence of fuel-cycle services under international control reduces the need and justification for independent national development of production facilities. Others believe that national R&D activities may be stimulated. Three related measures deserve specific attention: international fuel-service centers, which contain facilities for fuel processing, fabrication, and other services; careful management of fresh and spent recycle fuel to eliminate unnecessarily long periods when it is out of the reactor or not under international control; and reducing the number of transportation links and securing those that remain to minimize the risk of diversion, theft, or sabotage.

Fuel-Service Centers would operate a variety of facilities, including those required for the recycle fuel cycle (reprocessing, fabrication, and possibly colocating them) as well as those associated with other cycles (enrichment, heavy-water production). For the recycle reactors, such centers would place under international control those facilities with the capability for producing weapons-usable material; these are also the same facilities that are particularly difficult to safeguard effectively. Moreover, international centers, perhaps initiated as multinational ventures, would serve to increase the degree of interdependence of national nuclear systems and provide an opportunity for renewed commitment to the development of nuclear energy in a way that would limit the attendant risk of nuclear proliferation. Although

such centers remove sensitive facilities from national control, they may provide a means of further spreading sensitive technologies.

Fuel-Management Practices would be carefully designed in conjunction with fuel-service centers or whatever other facilities might provide fresh fuel and receive spent fuel. The objective of fuel management, from the point of view of proliferation resistance, would be to provide the greatest possible control of sensitive materials in order to reduce the risk of diversion from the fuel cycle. Fuel management practices would serve to reduce the out-of-core plutonium material inventory, a reduction which would also be an economic advantage. These practices could help to limit existing stocks of separated plutonium and lead to a system to minimize and control its storage or transport.

Transport Control would be designed to reduce the vulnerability of the system to seizure of materials in transit. Colocation of facilities in fuel-service centers would, of course, reduce the need for transport, often of the most sensitive materials, between such facilities. Careful fuel management would also be tied closely with improvements in transportation control. The general goals of transportation control would be to improve transport techniques to increase the difficulty of seizure.

Each of these measures may be supported by the technical improvements discussed above. For example, producing coprocessed and possibly pre-irradiated fuel in a fuel-service center under multinational or international auspices could lead to a system in which only reactors, short-term spent-fuel storage facilities, and the fuel itself are dispersed outside the center, and in which the fresh fuel bears some similarity, in terms of the radiation barrier, to spent fuel.

2.2.2 Alternate Recycle Systems

Some alternate systems under consideration include plutonium recycle in improved LWR's and in HWR's. The resistance of these cycles to abuse would be essentially the same as for the reference recycle system.

Alternate systems that rely on thorium as the principal fertile material are being considered both to decrease consumption of natural uranium and to increase the potential availability of "denatured" fuels. Denatured fuels are a mixture of uranium and thorium in which enough U-238 is present that the uranium itself, even if separated from the thorium, has sufficiently low fissile content to preclude its use in weapons without further enrichment. The fissile content of this uranium may be either U-235 feed from natural resources or U-233 from the conversion of thorium. These alternatives, many of which are independent in nature, involve various combinations of thermal or fast-breeder reactors to produce U-233 and others burning the denatured U-233 fuels.

All basic thermal-reactor types can be adapted to operate on denatured fuels. The ultimate value of denatured systems for proliferation resistance would be far less dependent on the proliferation resistance characteristics of the denatured fuel itself than on the effectiveness of international controls or limits on the deployment of sensitive facilities.

Denatured uranium-thorium recycle systems have three basic nonproliferation advantages: fresh denatured fuel requires that any uranium extracted from the fuel be further enriched to yield weapons-usable material; fresh denatured fuel has an inherent radiation barrier because there are products of radioactive decay of U-232 that accompanies U-233 (although this barrier can be removed for a few days by chemically separating the decay products); and spent denatured fuel has lower plutonium content than ordinary LWR fuel (because thorium replaces much of the U-238 in the fresh fuel) and has a substantial radiation barrier. However, there are also three nonproliferation disadvantages in contrast to LEU fuels: recycle is necessary and, in many cases, separated U-233 or HEU would exist somewhere in the cycle to increase the fissile content of the recycle fuel to the required level; enriching U-233 in denatured fuel requires less separative work to achieve high enrichments than does enriching U-235 in LEU to the same level of enrichment; and the fast critical mass of U-233 is three times less than that of U-235 and about the same as that of plutonium. The net result of these factors is that the number of centrifuges required for obtaining the same number of critical masses of U-233 and U-235 from denatured fuels would be at least ten times less than for natural uranium. A program to develop an isotopic separation capability would still be required, a formidable task for many nations.

Since denatured U-233 fuel cycles necessarily involve reprocessing and recycling, they have many proliferation vulnerabilities similar to those

of plutonium fuel cycles because of the deployment of reprocessing and fabrication plants. When only reactors are deployed at dispersed locations, denatured U-233 fuel is more proliferation-resistant than plutonium-recycle fuel but somewhat less resistant than once-through LEU fresh-fuel. There is no proliferation-resistance advantage in having denatured U-233 fuel in locations where recycle is permitted because there would still be substantial amounts of plutonium liable to seizure. The more complex the system of dispersed but interdependent reactors, the more difficult the arrangements to implement them. Such considerations favor LEU-fueled over denatured U-233/thorium-fueled reactors if reactors alone are to be deployed at dispersed sites and recycle facilities are to be deployed in suitable locations. An additional feature of the denatured U-233 fuel cycle is that reactors cannot be supported on denatured fuel at dispersed sites to a major degree for several decades because that time would be required to build up adequate inventories of U-233.

In contrast to such denatured systems, some advanced recycle systems, discussed below, may rely on HEU fuel. Such systems, like the light-water breeder reactor (LWBR), would probably be low in proliferation resistance, although perhaps comparable to the reference recycle system, which uses plutonium in the fresh fuel. Like the reference recycle system, the proliferation resistance of systems using HEU might be improved somewhat by spiking and by confining enrichment, reprocessing, and fabricating activities to plants under international control.

The LWBR concept is an attempt to exploit the breeding of U-233 while taking maximum advantage of the existing LWR technology base. The U-233 must be produced initially in prebreeders, that is, LWR's with cores designed to use moderately or highly enriched U-235, or plutonium as fuel but with thorium as the fertile material. The breeder concept depends on having HEU fuel in its breeder phase; the use of denatured fuel would preclude breeding, and the LWBR would then function as a high-gain converter. Since the prebreeder/breeder LWBR fuel-cycle systems require reprocessing and depend on the recycle of highly enriched U-233, their proliferation resistance would certainly be no greater than that of the recycle system if they were deployed under national control in NNWS's. The denatured U-233 high-gain converter concept would have the same proliferation characteristics as other denatured cycles requiring reprocessing.

2.2.3 Summary of the Proliferation-Resistance Assessment of Recycle Systems

A system based on conventional PUREX reprocessing of spent fuel from LWR's was chosen as the reference recycle system. An examination of the potential pathways to weapons through abuse of this cycle found three important technical vulnerabilities in addition to those present in the reference LWR once-through system. The first is that material would appear in transit and in national facilities in weapons-usable form and in forms that are relatively easy to exploit for weapons purposes. The second is that the relatively large commerce in plutonium-bearing materials, often in bulk form, would be difficult to safeguard effectively. The third is that reprocessing and MOX fuel-fabrication facilities which provide training and experience in plutonium extraction and handling techniques are deployed. These facilities may be attractive as civilian starting points for a nuclear-weapons program or provide an enhanced capability for an independent military program already deployed. These vulnerabilities and an evolving situation in which many countries have acquired preliminary experience with this technology, some of which (although fewer and with less urgency than in the recent past) indicate an intention to recycle, have pointed to an urgent need for strengthened technical and institutional controls. Accordingly, a wide range of potential technical, safeguards, and institutional improvements were examined.

Technical Measures

Coprocessing to eliminate directly weapons-usable material from the fuel cycle would significantly reduce the vulnerability to theft. While the operator of the plant could easily modify the plant to produce a pure plutonium stream, the detection by IAEA safeguards of pure plutonium anywhere in the cycle could provide evidence of a violation, were there an appropriate agreement.

Co-conversion by blending the originally separated uranium and plutonium nitrates would eliminate separated plutonium oxide from the cycles and provide protection against theft similar to that for coprocessing.

The introduction of a radiation barrier has been considered in order to provide a level of protection to plutonium fuels similar in nature to that of spent fuel. Radiation levels on the order of tens to a hundred rem/hr at one meter have been judged sufficient to force a nation seeking to produce tens

of weapons to conduct processing in an out-of-system facility similar to a spent-fuel reprocessing facility. This level of protection would correspond to that of spent fuel 100 to 150 years after discharge from the reactor. This radiation barrier could be introduced in a number of ways: spiking, in which a highly radioactive material such as Co-60 could be introduced at certain points in the reprocessing, conversion, or refabrication plants; partial decontamination, in which the reprocessing plant is designed so that a portion of the fission products always remains associated with the plutonium (since use is made of the relatively short-lived fission products in the spent fuel, this measure can be effective only for the processing of spent fuel discharged recently from the reactor); and pre-irradiation, in which the MOX fuel element is irradiated before shipment to the reactor site. None of these measures would seem to have much effectiveness against abrupt diversion at the national level in those realizations where a country has a reprocessing plant deployed, since it appears that the plant could be readily modified to produce plutonium in a pure form. Partial decontamination may be somewhat more effective than spiking in this respect since it would be easy to stop adding the spikant. However, a radiation barrier could delay weapons production by many months if out-of-system facilities have to be built. All of them except pre-irradiation may have some advantages with regard to protection against covert diversion by nations, and all of them would provide added protection against theft by the less sophisticated subnational groups. These advantages, however, would have to be evaluated in the light of the technical problems associated with them and of economic, environmental, and safeguards disadvantages. Other concepts involve various engineering design features, for example, to reduce accessibility to plutonium and, more speculatively, to incorporate active measures to deny the use of materials or facilities. None of these concepts appear to be more effective than those concepts already described in addressing the fundamental proliferation vulnerability presented by national control of reprocessing and refabrication facilities. Moreover, since many of these measures involve plant design, they cannot easily be retrofitted to existing facilities.

Safeguards and Physical Security

The IAEA has concluded that current material accountability is not adequate for the large reprocessing plants which are planned to come on line in the next few decades. Increased reliance will have to be placed on containment and surveillance measures, and the IAEA believes that there are good prospects that its goals can be met when specific new measures have been developed for materials accounting as well as containment and surveillance. It appears,

however, that these measures may be expensive to implement for the IAEA and the operator, and will require a politically significant level of intrusiveness into facility operations. Moreover, until there is a large-scale demonstration, uncertainties about the technical effectiveness of these measures will remain. Designing new reprocessing and refabrication plants to enhance the application of safeguards is both desirable and important, and can be facilitated through the design review procedure to be exercised by EURATOM and IAEA. The introduction of a radiation barrier would introduce serious difficulties in applying material accounting methods. In addition, inspection and verification would be difficult to carry out in plants in which the highly radioactive environment of the front end was extended throughout the reprocessing facility. And many of the new safeguards measures and procedures under R&D in the U.S. would be rendered inoperative and others less effective.

Adequate physical security measures are required to prevent diversion by subnational groups. Some of the technical (e.g., coprocessing) and institutional (e.g., colocation) measures considered may effectively contribute to reducing this threat, but their costs and benefits have not been fully evaluated.

Other Institutional Measures

One route to reduce the risk of abuse of nuclear fuel-cycle facilities is the development of internationally agreed-upon institutional measures. Basically, the proposals relate to placing sensitive materials and facilities under some form of international control.

One measure would be the construction and operation of only a limited number of large, nationally managed reprocessing plants which, apart from reprocessing fuel for domestic customers, would also provide a reliable reprocessing service on a competitive basis for customers in other countries. This measure has the advantage of limiting the sensitive fuel-cycle facilities to a few sites and nations. Such plants would incorporate advanced instrumentation, and design and other features to facilitate safeguarding. The deployment of the fuel cycle in other countries would be limited to the more resistant elements of the cycle, namely, the reactor and the uranium fuel-fabrication facility.

Several measures for multinational participation in nuclear fuel-cycle facilities have advantages and disadvantages like those already discussed, but there are additional considerations. Depending upon their characteristics, these measures may be coupled with stronger "political" barriers against the host nation's abrogating safeguards and with increased assurances that none of the participating nations had diverted material without detection. However, such multinational ventures might facilitate the spread of sensitive technology. While colocation of the reprocessing and MOX fabrication plants might make the fuel cycle less vulnerable to subnational theft by reducing transport requirements, it would have little or no impact on proliferation at the national level except to the extent that safeguards measures may be more effective at an integrated site and indirectly contribute to a trend toward reliance on fewer, larger facilities. This trend may result in fewer nations' possessing sensitive facilities.

Plutonium storage and management schemes which would provide for some form of international control over stocks of separated plutonium have been proposed. The advantages of such proposals are that excess plutonium would be removed from national control and its return would be subject to strict release criteria and international oversight.

The results of these assessments are summarized in Table 2.2-1.

Alternate recycle systems have also been examined to assess their relative proliferation resistance features. Modifications to the LWR or to plutonium recycle in HWR's would be essentially similar to the reference system. Advanced recycle systems typically incorporate thorium to reduce consumption of uranium resources and to make the denaturing option available. Adoption of a relatively pure uranium-thorium cycle (with U-233 and no U-238) would have proliferation risks comparable to those of ordinary plutonium-recycle systems since fissile concentrations would be comparable and since weapons-usable material would become available through chemical separation (hot reprocessing if the material is protected by a radiation barrier).

However, proliferation resistance may be increased if the fresh fuel is denatured. Isotopic enrichment would then be required to obtain weapons-usable U-233. Reprocessing and other recycle facilities could be placed in international centers operating in suitable locations under appropriate controls. In these centers, the extracted plutonium could be combined with

Table 2.2-1. Evaluation of Measures to Improve Proliferation Resistance of Closed Fuel Cycles

Measure	Proliferation Resistance Using UnSafeguarded Facilities or Materials	Proliferation Resistance Using Safeguarded Facilities or Materials	Effect on IAEA Safeguards	Proliferation Resistance to Subnational Threat
Co-conversion	Little or no change		Little or none	Increased
Coprocessing	(Increased)**	(Increased)**	Little or none	Increased
Pre-irradiation	(Increased)*	(Increased)*	Little or none	Increased
Spiking	(Increased)*	Increased)*	Degraded	Increased
Partial processing	(Increased)**	(Increased)**	Degraded	Increased
Passive measures and physical barriers	Little or no change	Increased	Enhanced	Increased
Active-use denial	Not applicable	Increased	Little or none	Increased
Fuel-Service Centers (including colocation)	Little or no change	Increased	Enhanced	Increased
Fuel-management and transport control (including storage/ transport as mixed oxide or mixed-oxide assemblies)	(Increased)*	(Increased)*	Little or none	Increased

*May not be very effective where reprocessing plant is deployed.
**Depends on how easily the facility can be modified to produce pure Pu stream.

thorium to fuel reactors which could then produce U-233. This U-233 would be denatured and used to fuel dispersed reactors, which would return their spent fuel to the international centers. But this system, which would require recycle facilities and interdependence between two reactor types, would not be preferable from a proliferation-resistance standpoint to an interdependent system which has reactors operating on LEU fuel in dispersed locations and returning spent fuel to international centers. It would be preferable to a system which used MOX to fuel the dispersed reactors.

It has also been suggested that special nuclear materials (SNM) can be "downgraded" to inhibit use in nuclear weapons by enhancing the emission rate of alpha particles, gamma rays, neutrons, or heat. Judgments about the use of SNM must depend on a detailed knowledge of nuclear-weapons design and testing. Although producing such details would conflict with U.S. nonproliferation policies, three conclusions can be drawn:

- U-233 is, in principle, as weapons-usable as U-235 or Pu.
- Increasing the emission rate of neutrons in U-233, U-235, or Pu would not preclude their use in weapons. This conclusion also applies to the presence of Pu-238.
- The presence of U-232 in U-233 does not provide effective protection against misuse.

What is required is the progressive introduction of features that will substantially improve proliferation resistance in order that, if recycle is introduced into widespread use, it should be possible to avoid large differences in proliferation resistance compared to that of once-through systems. Until these measures are developed, however, recycle would introduce the proliferation vulnerabilities already described.

Since LWR's are already widely deployed, it is possible that the recycle system could also become widely deployed. However, the effectiveness of combinations of technical and institutional measures to improve the proliferation resistance of the recycle system, as well as their feasibility and acceptability to nations considering the use of closed cycles, is difficult to predict in advance of their actual negotiation and implementation.

2.2.4 Fast-Breeder Systems: A Summary Account

Overview

Fast-breeder nuclear-power systems closely resemble recycle nuclear-power systems in the sense that spent-fuel reprocessing and recycle of fissile material are intrinsic features of the fuel cycles. Both systems require the same types of ancillary facilities for temporary spent-fuel storage, reprocessing, fuel fabrication, waste management, and transportation. The major differences between breeder and recycle systems lie in the greater flows at higher concentrations of plutonium in the fast-breeder system and in the reactors themselves. Current FBR designs would produce an excess of plutonium and could lead to the evolution of a nuclear economy which relies almost exclusively on plutonium for the fissile content of the fuel, whereas an economy based on recycle reactors must continue to rely heavily on uranium.

The reference fast-breeder is illustrated in Figure 2.2-3.

At present, no fully commercialized fast-breeder reactors are deployed. Rather, fast-breeder programs are under way in a small number of countries--most notably, Britain, France, Japan, Russia, United States, and West Germany--and are at various stages of development ranging from pilot and demonstration reactors to small research and fuel-cycle facilities to support fast-breeder system R&D. There is also a variation in the institutional context in which these programs are situated. Some, for example, are not subject to IAEA safeguards, and some envision a complete in-country fuel cycle while others do not.

The major impetus for reprocessing spent fuel at the present time, in addition to the management of spent fuel, appears to be for fast-breeder reactors (FBR) rather than for recycle reactors. Processing of spent fuel is expected to build inventories of plutonium compounds which can be used to start up FBR's during the transition period to FBR equilibrium. Plutonium for startup and refueling of planned breeders in Britain and France will come from gas-cooled reactor (MAGNOX) spent fuel and, in France, from LWR spent fuel as well. French plans call for a 100-T/yr plant to be commercial by about 1990, but this would serve only about 3 GWe of FBR capacity. The cumulative

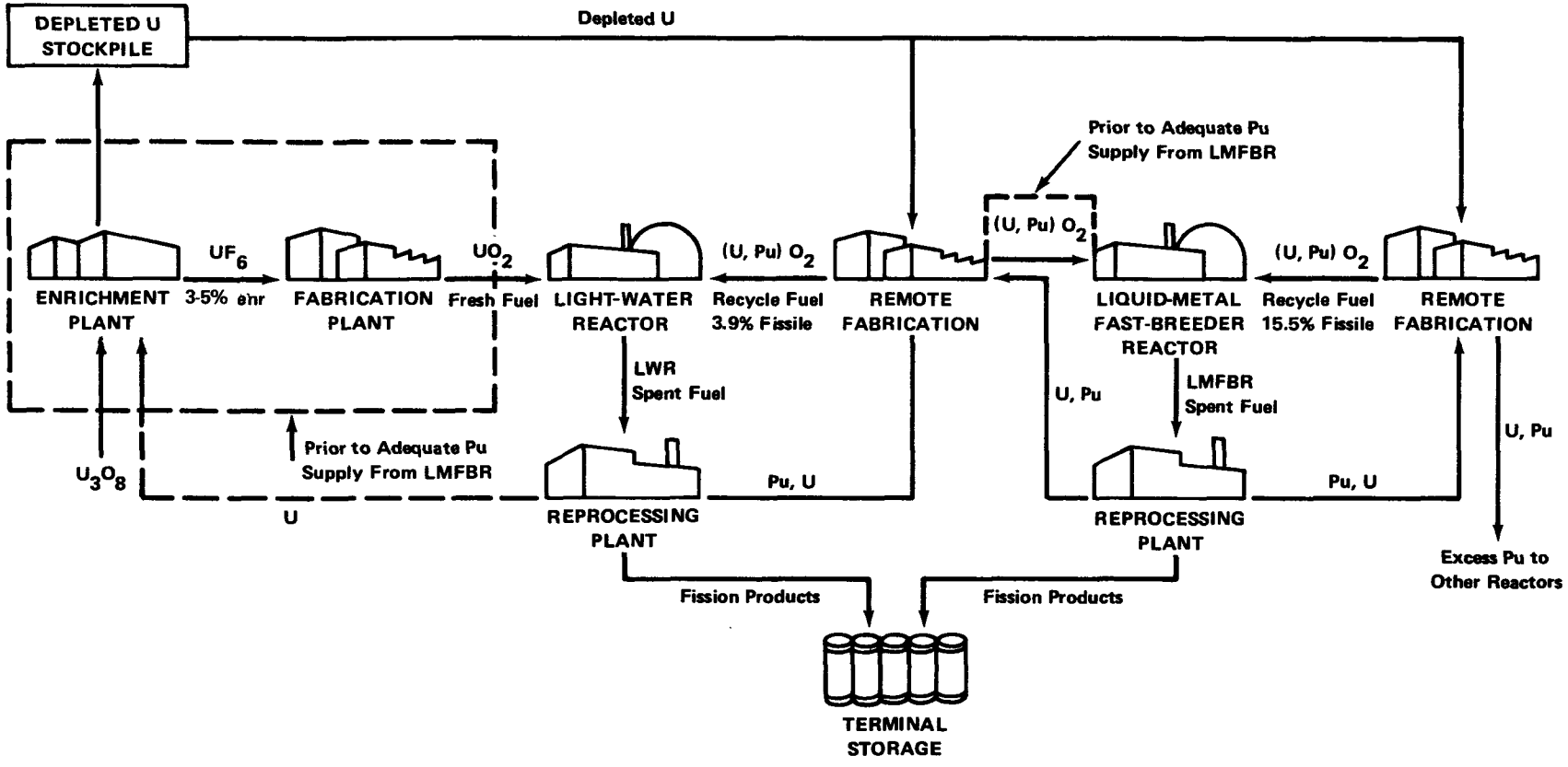


Figure 2.2-3. Reference Fast-Breeder System

plutonium production in thermal-reactor spent fuel in Japan and West Germany, as well as the reprocessing capacity to separate that plutonium, far exceeds their pre-2000 fast-breeder needs. However, if Japan's plans for a rapid transition to an all-breeder economy by 2025 materialize, this excess reprocessing capacity and perhaps more would be needed to meet those plans unless alternative sources of plutonium are found. A number of other countries are conducting research in fast-reactor fuel reprocessing. Aside from several European countries and Japan, India is apparently the only country with near-term reprocessing plans directed toward future support of FBR development. India plans to develop plutonium-thorium FBR's.

Most countries' plans for nuclear power through 2000 call for the deployment of LWR's. In 2000, less than 5% of the installed nuclear-power capacity outside the centrally-planned economies is expected to be FBR's. Most of this capacity will be in France, with some possibly in Britain, Japan, and West Germany, and perhaps Italy and India. Belgium, Italy, and the Netherlands have financial interests in the French and German FBR programs. It is against this background of FBR plans that the proliferation resistance of a reference FBR system is assessed.

Reference Fast-Breeder Fuel Cycle: Liquid-Metal Fast-Breeder Reactor

The reference fast-breeder system is the liquid-metal fast-breeder reactor (LMFBR). The facilities and materials appearing in the LMFBR fuel cycle are analogous to those of the reference recycle system discussed in Section 2.2.1. The most important proliferation-related features of either fuel cycle stem from the large-scale processing operations and commerce in plutonium-bearing materials. In a typical 1000 MWe LMFBR, for example, the total plutonium inventory in the core is about 5000 to 6000 kg. Yearly, approximately 2000 kg of plutonium is introduced into a one-gigawatt LMFBR, and about 10% more is withdrawn. For each such reactor, at least 2500 kg (probably several times more) plutonium would be in process, storage, or transport at any given time; by comparison, about 250 kg of plutonium is discharged in spent fuel from one gigawatt-year's operation of a once-through LWR.

Since facilities and materials are similar to those of the recycle system, the LMFBR system presents, within a given national context and deployment configuration, essentially the same opportunities for facility modification or for diversion of materials for out-of-system conversion. With the exceptions

noted below, the associated proliferation features and activities, and improvements have been discussed in connection with the reference recycle system in Section 2.2.

Figure 2.2-2 illustrates the proliferation pathways of the reference fast-breeder system.

A significant difference between LMFBR MOX and recycle MOX fuel materials lies in the fact that LMFBR fuels would have plutonium concentrations of 15 to 25%, which are considered to be weapons-usable, whereas recycle fuels would contain only 4 to 6% plutonium. Consequently, it is theoretically possible that a nuclear device could be made directly from fresh LMFBR fuel without the need for chemical separation; in recycle systems, PuO_2 itself is the only material that is weapons-usable. This feature would increase the vulnerability of the LMFBR system to subnational proliferation threats, particularly in countries deploying only the reactors. It would also increase vulnerability to national threats, although most nations would probably employ out-of-system facilities to recover plutonium metal.

Otherwise, the high plutonium concentrations and other minor technical differences between breeder and recycle fuels would have a slight impact on out-of-system proliferation activities. The higher plutonium concentrations, for example, would permit somewhat smaller facilities and less feed material to recover plutonium at a given rate. Spent fuel from an LMFBR core is accompanied by higher radiation fields than spent LWR fuel, while that from the blanket would be less radioactive. Both core and blanket spent fuel, however, would still require remote processing. Depending on the point of diversion, out-of-system facilities for processing spent LMFBR fuel might have to provide for removal of sodium or other liquid-metal coolant from the assemblies. While these differences are perhaps worth noting, their impact on the proliferation resistance of the LMFBR system is marginal.

Further proliferation implications of fast-breeder systems are related to the dynamics of system development. Whereas recycle systems with LWR's could be deployed relatively soon, LMFBR's cannot be deployed commercially on a major scale for at least two decades and possibly much longer. Changes in the international institutional framework within which nuclear-power systems are operated will clearly evolve during the period of development. However,

current reprocessing facilities and plans for their expansion are largely motivated by anticipated fast-breeder needs. In other words, the proliferation vulnerabilities of fast-breeder systems appear long before actual reactor deployment and must be accommodated in current efforts to establish a satisfactory nonproliferation regime.

Alternative Fast-Breeder Systems

Among the most important alternative fast-breeder fuel cycles from a nonproliferation point of view are those employing thorium as a fertile material. The potential nonproliferation benefits of thorium breeders arise from the fact that the fissile material, U-233, can be isotopically diluted with U-238 and used to replace U-235 as fuel in many types of reactors. An isotopic enrichment process is required to recover weapons-usable material from fresh fuel.

Thorium-breeder systems require the same generic fuel-cycle components as do the reference LMFBR systems. Thorium chemistry leads to differences in the specific details, but the basic processes are conceptually quite similar to those for recovering plutonium compounds in the reference LMFBR system. There is less experience with these processes, particularly on a large scale.

Denatured U-233 used as the fissile material in thorium breeder cores, either alone or mixed with thorium, would impose an isotopic barrier on the fresh fuel. Because of the U-238 denaturant, however, large amounts of plutonium would be produced, but the concentration in spent fuel would be about 4%, much less than the roughly 15% concentration in the reference LMFBR system.

Since U-233 does not occur naturally, the initial charges would have to be produced in converter, or pre-breeder, reactors. Alternatively, plutonium could be used as the fissile material. The initial stock could be obtained from reprocessing of LWR spent fuel. The plutonium could be mixed with U-238 or with thorium. In the former case, the fresh and spent fuel would resemble that of the reference fast-breeder system. In the latter case, the spent fuel would contain both U-233 and residual plutonium, with about 10 to 12% total fissile content. In neither case would an isotopic barrier be present.

The basic thorium-breeder concept implies that thorium would be the primary constituent of the fertile blanket fuel. If thorium alone were used, however, U-233 would be bred in highly enriched form and could be recovered in in-system or out-of-system chemical reprocessing plants. If thorium were mixed with U-238, however, the bred U-233 would be denatured in situ and thus supplement the radiation barrier in blanket assemblies with an isotopic barrier. Although plutonium would be produced, less would be produced than if it were in an all-uranium blanket.

If thorium breeders were to use plutonium as the fissile material in core fuel or if thorium alone were to be used as the fertile blanket material, the proliferation resistance of thorium breeders themselves would be qualitatively similar to that of the reference LMFBR's. The two systems provide analogous diversion opportunities, and the scope of out-of-system recovery operations would be comparable.

Interest in thorium-fueled FBR's arises particularly in connection with their use in interdependent systems that also include thermal reactors using denatured fuel. For example, one conceptual system would incorporate an FBR that supplies U-233 for thermal reactors using denatured fuel while at the same time consuming plutonium in its core. Arrangements like these, with U-233-fueled breeders or plutonium-converting breeders, would still have higher fissile concentration than once-through systems and would depend on the operation of reprocessing plants.

The gas-cooled fast reactor (GCFR) represents an alternative breeder technology which can operate on either uranium-plutonium or uranium-thorium fuels. This system requires reprocessing facilities with the same proliferation vulnerabilities as the reference LMFBR system. The net production of plutonium per GWe-year of operation is approximately the same as that of the reference system utilizing uranium-plutonium fuel. Consequently, this system offers no nonproliferation advantage over the LMFBR.

2.3 RESEARCH REACTORS AND CRITICAL FACILITIES

2.3.1 Proliferation Features and Activities

Although the above discussion of proliferation resistance has centered on nuclear-power plants, research reactors are also a potential source of weapons-usable material.

Research reactors are typically used to study the irradiation behavior of materials of interest in nuclear engineering; to produce radionuclides for medicine, industry, and agriculture; and to promote basic research and teaching. The proliferation implications of research reactors arise from their widespread deployment and their use of potentially significant amounts of HEU as fresh fuel (typical annual fuel requirements are 0.6, 8.4, and 121 kg of HEU for reactors with thermal power levels of 1, 10, and 100 MW, respectively), while others using natural or LEU may produce significant amounts of plutonium in the irradiated fuel.

Critical facilities are very low-power experimental reactors (usually below 10_2 kilowatts) which operate at low neutron-flux levels (e.g., 10^8 neutrons/cm^2 sec) with no appreciable fuel burnup and little induced radioactivity in the fuel and other core components. They are used as simulators, to provide experimental confirmation of design calculations relating to various reactor characteristics, like critical mass, kinetics and control, and reactivity coefficients. Critical facilities for use in FBR research may use HEU or plutonium in various forms, including metal, oxide, and alloys. Since the fuel has little burnup or induced radioactivity, it is usually loaned or leased from the supplier to the operator. Critical facilities for breeder research use plutonium or HEU in quantities ranging from a few kilograms to a few metric tons.

2.3.2 Proliferation-Resistance Assessment of Research Reactors

HEU Research Reactors

To obtain sufficient material from a research reactor to build a nuclear weapon would require removal of a quantity of HEU comparable to the annual fuel requirement for a typical, large research reactor. For instance, a 20 MWth research reactor may have about 200 grams of HEU in each fuel element. About 60 fuel elements are needed as replacements each year. In this instance, more than a year's supply of fuel elements would have to be diverted to build a nuclear weapon. However, the fabrication of fuel elements for a given research reactor is normally performed on a special-order basis and may involve considerable lead times. In the absence of measures to minimize HEU inventories, typical procurements of fresh-fuel elements would require storage of several years' requirements at the reactor site. Significantly large quantities of HEU are also present at the fuel-fabrication facilities, but there are very few such facilities.

France, the United States, West Germany, and the IAEA have been engaged in studies aimed at preserving the scientific and research advantages of research reactors fueled with highly enriched uranium while reducing their proliferation potential. Some research work suggests that most research reactors can be adapted to less highly enriched uranium (from 20 to 40% U-235 with today's technology) with little effect on overall reactor performance. This result is accomplished by increasing the total amount of uranium present in the fuel elements. That is, the amount of U-235 is diluted in larger amounts of U-238. One of the approaches pursued by France is to develop a replacement fuel for its reactors which is 7% enriched uranium. Implementation of such technical measures would substantially diminish the proliferation risk associated with HEU research reactors and would permit the possibility of reduced physical security requirements to counter the threat of subnational groups. Operators should find these measures attractive since relatively free access is important for effective research at such reactors.

LEU or Natural-Uranium Reactors

Natural-uranium research reactors produce plutonium at the approximate rate of 1 gm/MWth/day of operation. A typical 20 MWth research reactor fueled by

natural uranium would produce about 5 kg of plutonium per year. The amount of plutonium produced is reduced as the enrichment level is increased. A 20 MWth research reactor using 10 to 20% enriched uranium would generate only about 0.5 kg of plutonium per year.

The proliferation resistance of spent fuel from research reactors would be similar to that from nuclear-power plants, with some exceptions. First, since the amount of radioactivity from research reactor spent fuel can be as small as one fiftieth that of fuel from a commercial power reactor, shielding problems may be less difficult to deal with. Second, since there are several different chemical forms that are typically used for research reactor fuel elements, the steps involved in the chemical reprocessing would be altered. Consequently, measures should be taken which diminish the proliferation risk associated with LEU or natural uranium research reactors. These measures will include technical nonproliferation improvements but will most likely be dominated by improved international safeguards for such reactors.

Improvements

Improved international safeguards and a more universal commitment to full-scope safeguards as discussed for nuclear-power plants would also be important for reducing the proliferation risks of research reactors. Safeguards procedures need to accommodate the necessary flexibility of research reactor operations.

A longer-term goal that would increase the proliferation resistance of research reactors would be the achievement of a mean level of enrichment of 3 to 20% for widely deployed research reactors. Such a level of enrichment would seem to put the greatest distance between research reactors and the problems of HEU on the one hand, and of plutonium in spent fuel on the other. Existing technologies can make significant improvements toward this goal.

Throughout the world, there are currently over 150 research reactors operating at greater than 10 kw power and requiring an annual supply of about 1200 kg of HEU enriched to about 90%. The resulting worldwide commerce to maintain fuel supplies for these reactors amounts to about 5 metric tons of HEU. With existing technology, approximately 90 of these reactors can utilize 20%

enriched fuel, and an additional 35 reactors can utilize 45% enriched fuel, without significant impairment of performance. With advanced technology, it is expected that all but five reactors, representing about 800 MW, can be converted to 20% enriched fuel, and those five should be able to convert to 45% (or less) enriched fuel. If so, worldwide commerce in this 90% HEU for research and test reactors could be cut at least in half. The development, demonstration, and implementation of these new fuels should proceed as research is continued for attaining the longer-range goal.

Converting these reactors will, of course, take time and result in substitution costs. However, there is, substantial international interest in this program. Finally, it would be useful to establish the norm that research reactors should not be built without a demonstration of a clear need for them.

Education and Training of Foreign Nationals

Another aspect of research and training which has potential implications for nuclear-weapons proliferation is the education and training of foreign nationals at educational institutions, government laboratories, and private companies. A consideration of the proliferation implications of the education and training of foreign nationals should take into account several factors.

First, basic principles for the design of nuclear weapons and, to some extent, engineering practice for enriching uranium by various methods and for reprocessing spent fuel have been available in the open literature for many years.

Second, to move beyond the stage of crude sketches and educated guesses to the design of a deliverable nuclear weapon, and the construction and operation of the facilities required either to process fuel-cycle materials to weapons-usable form or to pursue an independent path to weapons-usable materials require a broad base of trained personnel including physicists; computer scientists; nuclear, chemical, and mechanical engineers; and metallurgists. The exact spectrum of skills depends on the particular fuel cycle and the specific technologies selected.

Third, advances in computing techniques, hydrodynamics, equations of state, neutron-transport physics, and the like since World War II have made the task of reinventing the bomb today much easier than it was to invent it originally.

Fourth, the United States is not the sole source of expertise on nuclear weapons. In general, educational institutions provide opportunities to acquire basic knowledge in broad areas of science and engineering, while government laboratories and, to a lesser extent, private companies in the developed countries have the means of providing hands-on training in the design, construction, and operation of facilities for uranium enrichment, spent-fuel reprocessing, and heavy-water production. Other NWS, of course, also have facilities for the design, construction, and testing of nuclear weapons.

In light of the above, it would appear that guidelines on the availability of training in sensitive technologies at U.S. Government laboratories and private companies are required. It would appear desirable for other suppliers to establish similar guidelines.

2.4 COMPLICATIONS AND PROSPECTS FOR IMPROVEMENTS

Most of this volume, especially the first three parts of this chapter, emphasizes the proliferation resistance of the individual fuel cycles in isolation from each other. But it has not entirely overlooked the different realizations of each fuel cycle as deployed, for it has considered the national contexts in which some elements of the fuel cycle were deployed in one nation and were served by other elements, usually sensitive facilities in other nations. However, the present situation--not to mention the situation that is likely in the future--is even more complicated. At any given time, a variety of systems is likely to exist within many nations, and the elements in this variety will continue to change.

This volume has considered only some of the cases from the wide range of current national activities throughout the world. There are countries which have reactors only and rely on fuel supply services from other countries. There are countries which are in various stages of development and deployment of different elements of each fuel cycle. And, of course, there are other

nations, especially those with more advanced nuclear-power programs, which have all or most of the elements of the individual fuel cycles. In this context, the possible interrelationships among these fuel cycles must be considered since they may serve as different civilian starting points for the military fuel cycle. Two important questions to be answered are what is the significance of the differences described in the previous sections between the individual fuel cycles in the real world, and what is the significance of the development of different elements of each fuel cycle in the same nation. It has long been recognized that in the absence of appropriate controls, there are many potential overlaps between civilian and military nuclear fuel cycles. In order to explore these overlaps, it is useful to begin by reviewing briefly a few typically military fuel cycles shown in Figure 2.4-1. Four possible starting, or feed, materials and two weapons-usable materials, HEU and plutonium, are shown. There are six different pathways (numbered) shown for reaching the weapons-usable materials, two of which (1 and 6) are by direct procurement. The other four pathways depend on the feed material available and various required dedicated facilities (lettered). The output from these dedicated facilities is, of course, processed further and fabricated into weapons.

An enrichment facility (A) big enough to produce material for tens of uranium weapons a year would take hundreds of millions of dollars to develop and construct, and many years, several of which would first be spent on the necessary R&D stage. Its separative capacity would have to be half as big if LEU (2) instead of natural uranium (3) were used as feed.

A production reactor, which could be one of several different suitable designs (an LWR fueled by LEU [B] or a reactor fueled by natural uranium and moderated by graphite or heavy water [C]), would take several years to build and could cost from tens to as many as a hundred million dollars, depending on its size and the sophistication of design. Once operational, it would be hard to conceal.

A reprocessing facility (D) large enough to produce material for tens of plutonium weapons a year could take a few years to build and cost as little as tens of millions of dollars, depending on the sophistication of design. Because the fuel in military production reactors is irradiated to much lower burn-ups than in nuclear-power reactors, the reprocessing facility can be somewhat simplified. Small facilities to handle enough material do not have to be complicated (Section 3.2).

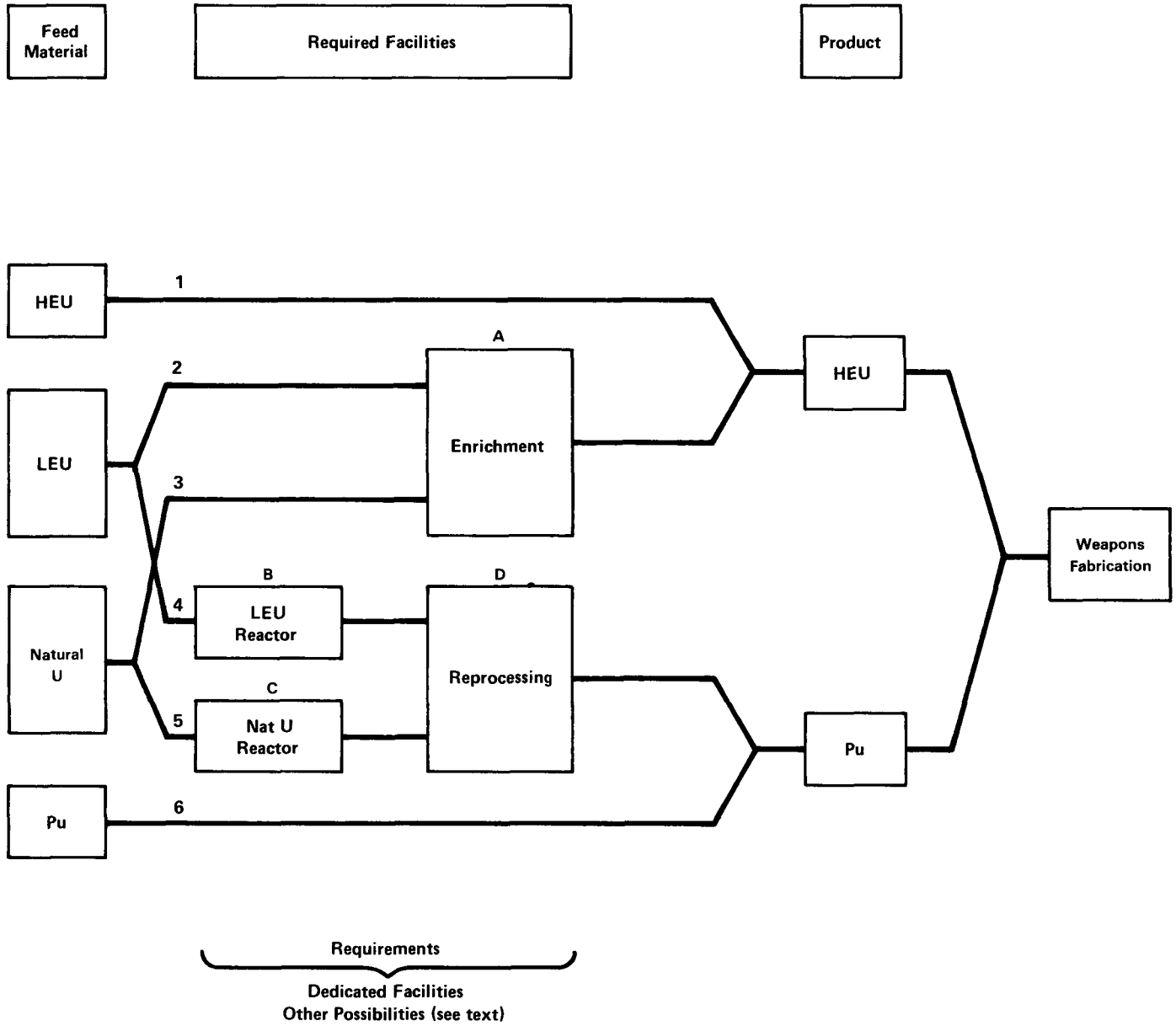


Figure 2.4-1. Proliferation Pathways: "Military" Fuel Cycles

The following paragraphs provide examples of overlaps between military fuel cycles and civilian fuel cycles. They show that some of the dedicated facilities required in the military cycle could be in-system facilities in a civilian cycle or that some of the out-of-system facilities required for abuse of one civilian cycle need not be the dedicated facilities of the military cycle but could be in-system to another civilian nuclear activity.

The out-of-system facility required for abuse of fresh-fuel feedstocks from the once-through fuel cycle could be the dedicated enrichment facility (A). Or it could be an in-system R&D enrichment facility intended to support an HEU power reactor or even an HEU research reactor. Or the natural uranium feed in the military fuel cycle (3) could be brought in as undeclared (unsafeguarded) feed into the in-system enrichment facility of the once-through cycle instead of the dedicated facility (A) of the military cycle.

The out-of-system reprocessing facility required for the abuse of the spent fuel from the once-through fuel cycle (Section 2.1) could be the dedicated reprocessing facility (D). Or this out-of-system facility could be an R&D facility (laboratory-scale, pilot-scale, or a demonstration facility) built in anticipation of the need for recycle or the fast-breeder fuel cycle or even a civilian-scale facility--in any case, an in-system facility for either of those fuel cycles (Section 2.2). Or it could be a suitably modified hot cell located at the site of a once-through reactor and normally used for examining failed power-reactor fuel elements.

The HEU for the military fuel cycle (1) could have been obtained from one of the critical facilities or as fresh fuel from a research reactor (Section 2.3). The plutonium for the military fuel cycle (6) could be obtained from a critical facility (Section 2.3) or as feedstock for fuel from demonstration recycle or fast-breeder fuel-cycle reactors (Section 2.2).

The dedicated production reactor (C) could be the natural uranium research reactor (Section 2.3). Indeed, large-tank HWR's are virtually indistinguishable on a technical basis from military production reactors. But a power reactor produces plutonium in spent fuel, too, and can be operated unobtrusively to produce weapons-grade plutonium.

It is quite evident that there are many potential civilian starting points for military fuel cycles and that some of the out-of-system facilities needed for the proliferation activities discussed for power fuel cycles do not, in fact, have to be military facilities at all but can be in-system facilities for civilian nuclear-power cycles or activities.

It is also clear that the differences between fuel cycles described in earlier sections are technical in nature only to a limited extent. Of much more importance is an institutional regime to maintain these differences. For example, enrichment services are now supplied by only a few nations. It is clearly desirable to find ways to maintain the nonproliferation features of this situation. Or again, the once-through cycle does not involve reprocessing, a technical difference from those cycles that do. Thus, the key proliferation activity is the construction of a reprocessing facility. When the construction of such a facility is required for another civilian fuel cycle, every possible effort should be made to ensure that the facility be designed in a manner at least not to increase proliferation risks above the level then existing. In fact, under the current full-scope safeguards regime, such facilities have to be openly declared to the IAEA.

By virtue of the direct access they provide to weapons-usable materials, certain R&D activities such as fast critical experiments involving large amounts of plutonium pose obvious proliferation risks. The potential misuse of research in enrichment--for example, that involving lasers and plasmas to develop effective methods of producing HEU--is also a proliferation risk. It is obviously unrealistic to expect that nations will forego all nuclear R&D involving sensitive materials, facilities, or technologies. But alternatives to undertaking such activities on an exclusively national basis, including opportunities for the use of existing nuclear facilities, could be offered on a cooperative basis. Moreover, other research activities will require diligent attention by members of the international community.

Because some R&D activities are especially worrisome, the question of how to deal with them must be considered. The nature of research makes its course difficult to predict as a practical matter. As a theoretical matter, it is undesirable to regulate or control research. However, in anticipation of the potentially undesirable consequences of research, societies do impose limitations on themselves from time to time. In ratifying the NPT, over 100 NNWS's have foresworn the development of nuclear weapons. It may be that, in less formal ways, certain activities otherwise legal come to be regarded as

politically unacceptable so that nations undertaking them stand in contravention of accepted norms of international behavior.

The design of the appropriate institutional arrangements should have the objective of providing for the fullest cooperative participation possible for all members in all R&D activities consistent with accepted nonproliferation norms. It would be beneficial to develop an international norm according to which all states would agree to limit enrichment activities to the production of LEU. A multinational organization for producing LEU (like EURODIF) which enables partners to share in the manufacture of components and the construction, operation, management, and ownership of enrichment facilities, and permits partners access to all but the most sensitive details of the technology itself, would be a distinct possibility.

Similarly, an approach involving multinational participation in existing breeder R&D activities could be an alternative to individual national programs. Here, detailed process information and personnel trained in reprocessing are already relatively much more available than they are in the case of enrichment.

Several large research reactors and critical facilities already exist, and ways to make the use of these facilities available on a cooperative basis could be explored.

A principal goal, of course, is to choose systems and activities that have a minimum of sensitive materials or technologies. But to the extent that such materials or technologies are present, whether in a commercial fuel cycle or in R&D activities, it is important that efforts be made to reduce their proliferation risks. In general, these efforts will require creation of institutions that make proliferation based on nuclear-power activities both technically difficult and politically infeasible or unattractive. It is difficult to predict whether such institutions will be developed, become operational, and be widely accepted by the time they are needed, but, as in the past, a cooperative approach will be required. In the meantime, an understanding of the risks resulting from their absence and of the benefits accruing from their establishment is essential to their acceptance. This subject is discussed in more detail in Volume VII.

3. ASSESSMENT OF ASSOCIATED SENSITIVE MATERIALS AND FACILITIES

The foregoing discussions have noted the degree to which sensitive materials, HEU and plutonium, and sensitive facilities, enrichment, heavy-water production, and reprocessing, are involved varies from one fuel-cycle system to another. A recurring theme has been that the amount of plutonium present, the form it is in, and the rate of increase in these different forms are all important factors in finding ways to reduce the proliferation risks of different fuel cycles.

Section 3.1 examines the proliferation resistance of seven different enrichment technologies. Some of these are currently deployed commercially, and some are in the pilot-plant stage. Others are under development because they may have proliferation resistance or economic advantages.

Section 3.2 examines the significance of accumulations of spent fuel and the plutonium that it contains in light of the pressures created to alleviate storage problems. Section 3.3 discusses the significance for proliferation of the different forms of plutonium at the back end of the fuel cycle. This section also describes the dedicated facilities needed to process the different forms of plutonium found at different points in the fuel cycle to weapons-usable form. Alternative processes are examined as ways to reduce the proliferation vulnerabilities of the back end of the fuel cycle.

3.1 ENRICHMENT

3.1.1 Introduction

At the present time, U.S. gaseous-diffusion plants, supplemented by small European centrifuge and diffusion plants, meet most of the uranium enrichment needs of the free world. In the next decade, an increase in centrifuge plant

capabilities, the deployment of a pilot plant using an aerodynamic technology, and the demonstrations of chemical exchange and radically new laser or plasma-based systems promise major changes in meeting these needs. Since enrichment is an essential component of most once-through fuel cycles, and all of the known enrichment technologies have a potential for producing weapons-grade uranium, the widespread deployment of enrichment facilities raises concerns about the possibility of proliferation. The primary concerns are:

- o The adaptability of commercial LEU plants to the production of HEU in the event of either:
  - A covert national attempt to produce and remove HEU from a safeguarded plant; and
  - An overt national diversion followed by a commitment to the fastest feasible weapons production.
- o The implications of each technology in enhancing a nation's capability to produce weapons-usable material in a dedicated facility.

The concern with a dedicated facility is examined in terms of the technical difficulty of designing, building, and operating the plant, and of the opportunities for its detection by the international community.

The remainder of this section surveys the leading technologies (in 3.1.2), considers the abuse of civilian or the use of dedicated facilities for each technology (in 3.1.3), briefly addresses the safeguards requirements (in 3.1.4), and summarizes the proliferation implications of enrichment technologies (in 3.1.5).

3.1.2 Overview of Technologies

The physical basis for separating isotopes includes direct exploitation of the atomic mass differences by centrifuge and aerodynamic processes, indirect exploitation of their effect on gas motions by gaseous diffusion, small differences in atomic or molecular resonances that can be excited by lasers, or minute differences in the nominally identical chemistries of isotopes. In this section, seven different technologies with proven or potential civilian

interest have been analyzed; this number includes a modern version of the World War II calutron electromagnetic separator, a possible technique for dedicated HEU production.

An overview of the leading enrichment technologies is given in Table 3.1-1, and their principles of operation are sketched in Figure 3.1-1. The elementary unit of a separation plant in most cases lacks the separation capability to separate natural uranium of 0.7% U-235 assay into an enriched product stream of about 3% U-235 assay and a depleted tails stream. Separating units are connected in parallel to form a stage, and stages are connected in series to form a cascade of the desired capability. The terminology is far from rigid: the plasma separation process (PSP) system performs its full enrichment in a single stage which is called a module.

Table 3.1-2 summarizes roughly comparable information about the seven enrichment technologies as used for LEU production. Equilibrium time is that required for the output rate to settle to a steady value after a disturbance of the input or control settings and is a measure of the time required to attain a new level of enrichment. Its value depends on the enrichment factor of each separation stage, the number of stages, and the specific inventory of the process. In two systems, gaseous diffusion and chemical exchange, the long equilibrium time is the determinant for the time needed to produce HEU. In the others, the time to produce a significant quantity is dominated by other system delays.

3.1.3 HEU Production in Civilian LEU Plants and Dedicated Facilities

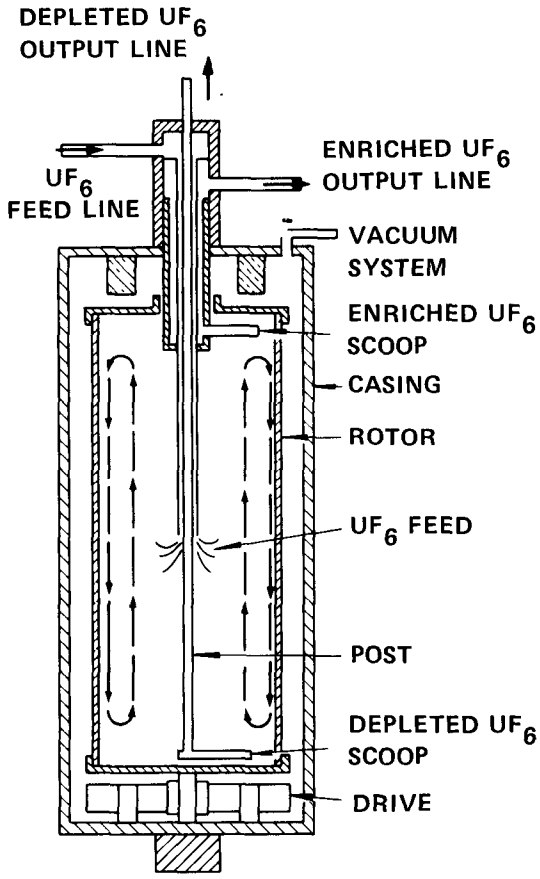
The low-separation-factor stages of the diffusion, centrifuge, and aerodynamic technologies can, at varying costs, be configured into very long cascades to produce HEU. One method of modifying a civilian plant would be to add large numbers of small stages. But there are a number of pathways to HEU which do not require more stages than those needed for enrichment to LEU. These pathways include batch recycling, or multiple passes, of the product, cascade reconfiguration, and modifying the operation, or "stretching," the cascade enrichment capability at the expense of an increased tails assay and decreased throughput in an off-design mode.

Table 3.1-1. Overview of Leading Enrichment Technologies as Used in LEU Production

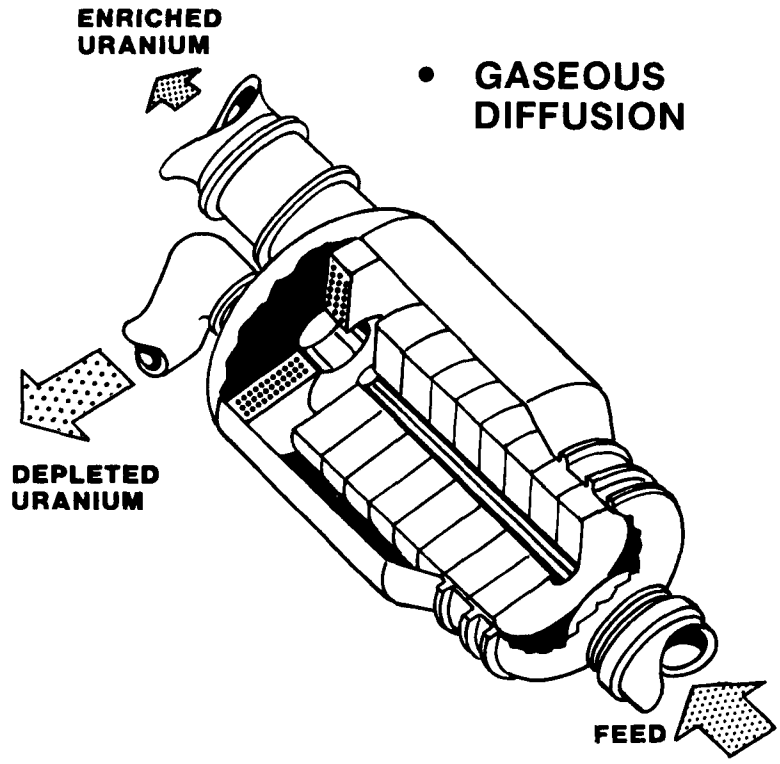
Technology	Period	Physical Principle	Present Implementation
Gaseous Diffusion	Late 1940's on	Differential U-235/U-238 rates of collision with permeable walls	U.S.: 21 million SWU/yr-1979; 28 million-1980's; EURODIF/ COREDIF: 22 million SWU/yr-1980's
Centrifuge	1940's R&D 1970's Implementation	Enhancement of centrifugal effect by countercurrent flow	U.S.: 8 million SWU/yr-1980's; URENCO: 1.2 million SWU/yr-1980; 10 million-1980's
Aerodynamic (Becker Nozzle)	1950's on	Centrifugal effects on UF_6 in very small curved-wall chamber	German R&D; Brazilian pilot plant 1980's; South African variant 1970's
Calutron	1940's	Mass-dependent deflection of ions by strong magnetic field	Oak Ridge 1944. very low throughput
Chemical Exchange	Concept dates from WW-II. Serious R&D in 1970's	Exploits isotope-dependent differential equilibria in a system of organic and aqueous uranium compounds	U.S., French, and Japanese R&D. No implementation yet
Atomic Vapor Laser Isotope Separation (AVLIS)	1972 on	Multistep ionization of uranium metal vapor by optical laser	R&D prototype in 1980's (part of AIS Program)**
Molecular Vapor Laser Isotope Separation (MLIS)	1972 on	Laser chemistry on UF_6 (supercooled through large expansion nozzle)	R&D prototype in 1980's (part of AIS program)**
Plasma Separation Process (PSP)	1975 on	RF reinforcement of orbits of uranium vapor ions in strong magnetic field	R&D prototype in 1980's (part of AIS program)**

*The capacity of an enrichment plan is given in separative work units (SWU's). This unit represents a measure of the work required to separate a gaseous mixture of isotopes into two components, product and tails, of different composition. Since the SWU has a thermodynamic basis, it is valid for comparing enrichment processes involving different technologies. In the U.S., SWU's are measured in kg SWU's but denoted merely as SWU's.

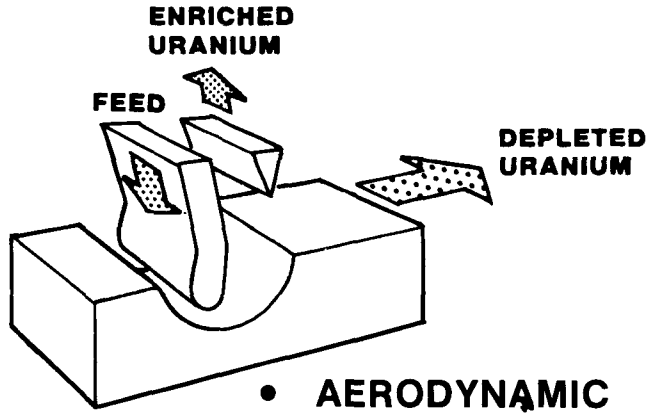
**Competition in the early 1980's will determine which of these prototypes of about 0.5 million SWU/year will be continued in the U.S.



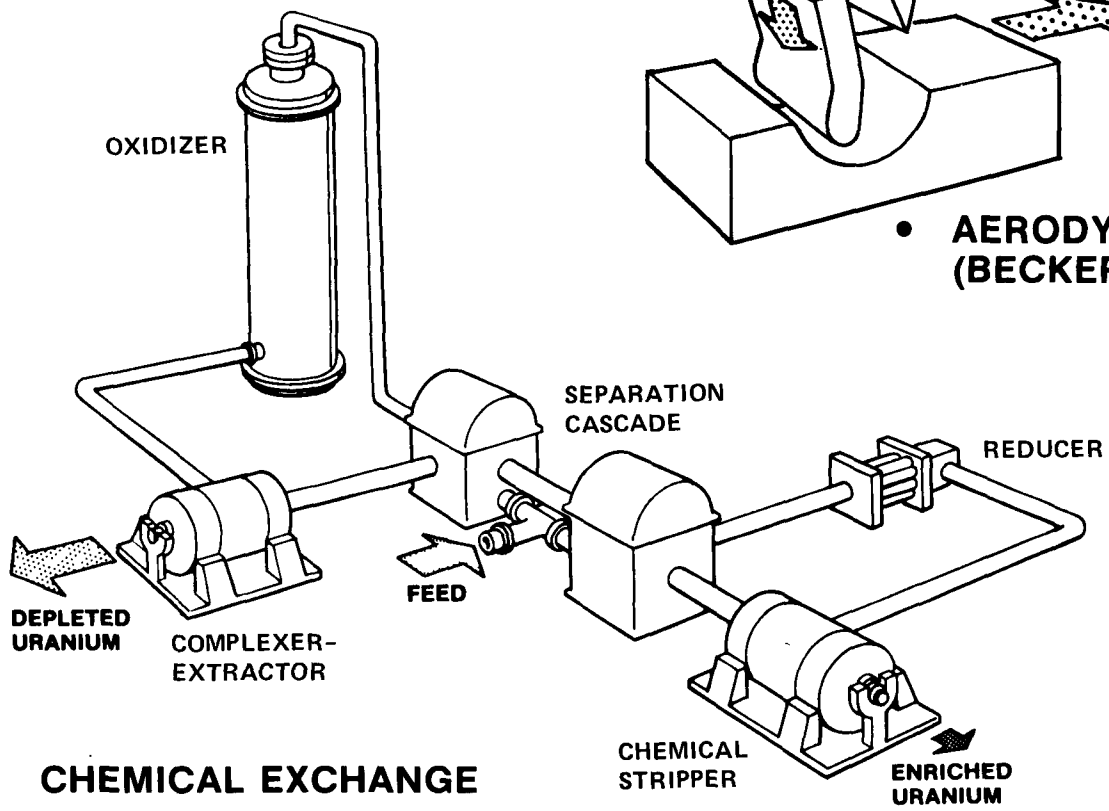
• CENTRIFUGE



• GASEOUS DIFFUSION

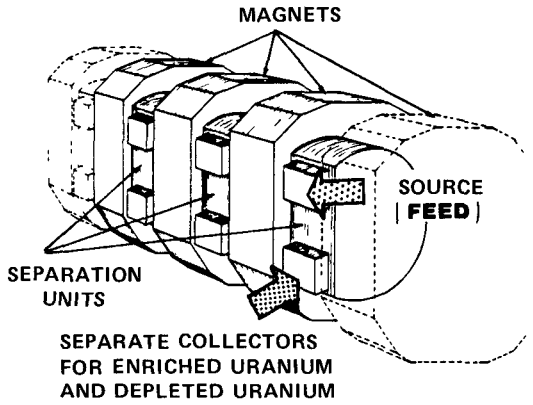


• AERODYNAMIC (BECKER NOZZLE)

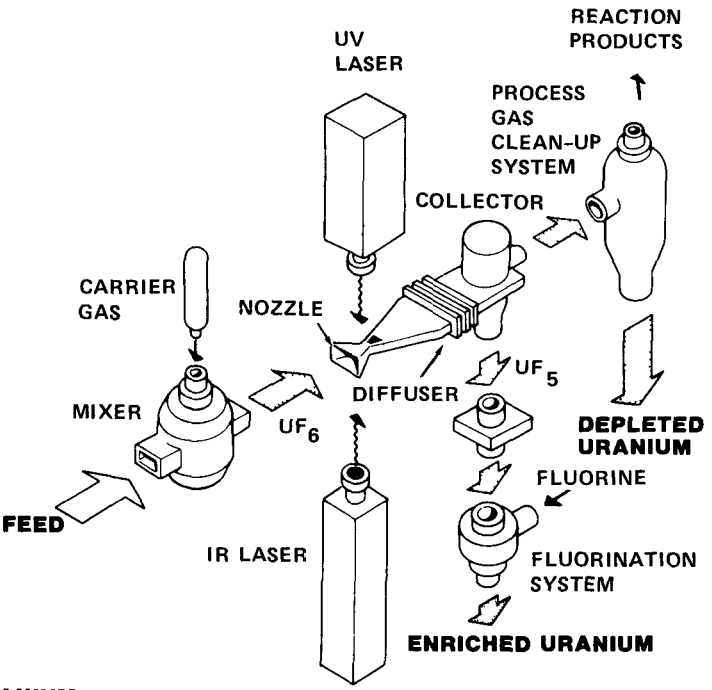


• CHEMICAL EXCHANGE

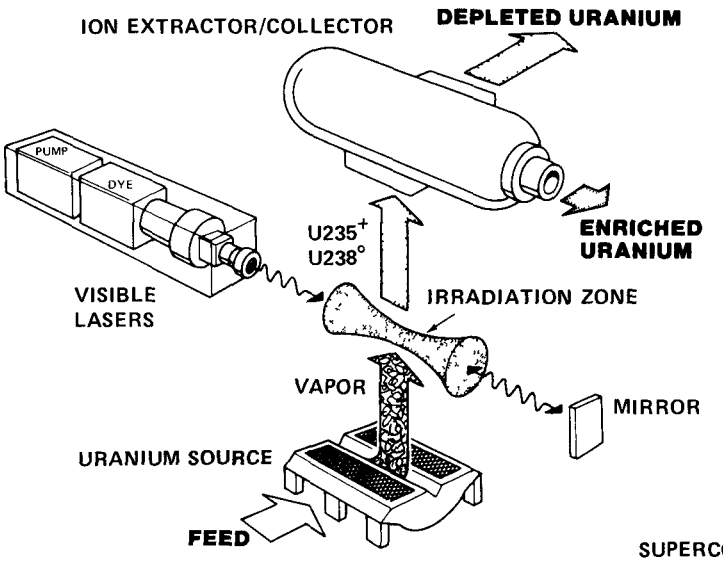
Figure 3.1-1 (a) Principles of Operation of Leading Enrichment Technologies



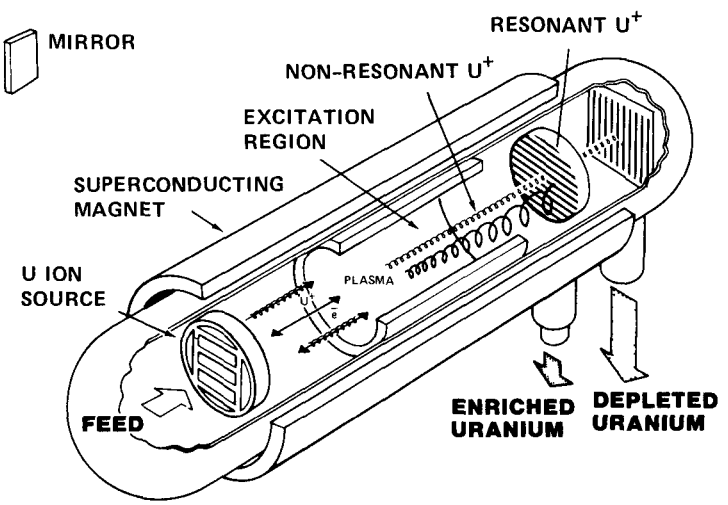
- **CALUTRON**



- **MOLECULAR LASER ISOTOPE SEPARATION PROCESS**



- **PLASMA ISOTOPE SEPARATION PROCESS**



- **ATOMIC VAPOR LASER ISOTOPE SEPARATION PROCESS**

Figure 3.1-1 (b) Principles of Operation of Leading Enrichment Technologies

Table 3.1-2. Technical Overview of Leading Enrichment Technologies as Used in LEU Production

	Typical Plant Size (10^6 SWU/yr)	Separation Factor (α)*	Units or Stages	In Process Inventory of LEU	Equilibrium or Holdup Time
Gaseous Diffusion	∿9	1.004	∿1200 stages	Thousands of tons	Weeks
Centrifuge	∿9	∿1.3	∿10 multiunit stages (1000's of centrifuges)	Tens of tons	Hours
Aerodynamic (Becker Nozzle)	0.2	∿1.015	400-600 multi-assembly stages	50 tons	∿1 day
Calutron	Non-commercial	∿400	Not applicable	Not applicable	Not applicable
Chemical Exchange	Planned up to 9	∿1.0015	∿3000 stages	Thousands of tons	Months-Years
Atomic Vapor Laser Isotope Separation (AVLIS)	Planned up to 9	∿10	∿14 modules in parallel	100 kg/module	Very short
Molecular Laser Isotope Separation (MLIS)	Planned up to 9	∿10	Few large modules	100 kg/module	Very short
Plasma Separation Process (PSP)	Planned up to 9	∿10	Single-unit modules	Tons/batch	Very short

*α is defined as the ratio of the product and tails assays. The enrichment factor (product/feed assay) is frequently designated β_1 and the depletion factor (feed assay/tails assay) is β_2. Thus $\alpha = \beta_1 \cdot \beta_2$.

In batch recycling, the cascade product is used as feed for subsequent cycles of enrichment. For example, a cascade designed to produce an LEU assay of 3.5% from natural uranium can be recycled to give the product assays shown in Table 3.1-3.

Table 3.1-3. Example of Batch-Recycle Schedule for LEU Plant

Cycle Number	Feed Assay % U-235	Product Assay % U-235
1	0.711	3.5
2	3.5	15.5
3	15.5	48.2
4	48.2	82.5
5	82.5	96.0

Batch recycle is feasible when cascade inventories are small and when criticality and other factors do not inhibit further enrichment of high-assay feed stocks. Accordingly, it is directly relevant to the centrifuge and aerodynamic technologies. But it is less practical for gaseous-diffusion and chemical-exchange technologies.

The reason is that the very large cascade inventory required by each recycle must be filled by the product of prior cycle; since the product yield is only about 20% of the feed, the time for overall enrichment would take years. For gaseous diffusion, the time required can be reduced by reducing the pressure of the gas in successive cycles. A penalty is associated with this reduction because the separative capacity is proportionately reduced. A similar strategy could probably be employed with chemical exchange by using successively more dilute concentrations of uranium.

Cascade reconfiguration to place more stages in series for HEU production may be feasible in a plant that contains enough units in parallel cascades to make up the necessary number of stages. In LEU diffusion plants of economical design, there are insufficient units to allow HEU production by cascade reconfiguration. However, a reconfiguration of an LEU centrifuge plant appears straightforward and can even be realized without disassembly of the individual cascades. For example, if four nominally parallel unit cascades

are series-connected, with the tails stream of each of the three upper units connected to a matched feed point in a lower unit, 80% enrichment is possible with a separative work loss of less than 5%.

Stretched operation exploits the fact that the assay gradient of an LEU cascade can be substantially increased by reducing the rate of product withdrawal; for example, a 1200-stage diffusion plant configured for a nominal 3% U-235 product can provide up to a 50% assay at the price of a much-reduced throughput and long equilibrium time.

Gaseous Diffusion

Abuse of Civilian Facilities -- In addition to batch recycle, which is time-consuming in a diffusion plant, there remain two methods for producing HEU. The first introduces an additional HEU cascade to enrich a fraction of the normal LEU throughput. Designs are available for small "rabbit" stages which recycle the product around each stage to obtain an enrichment factor that exceeds the single-pass value of 1.004 for the stage separation α. About 300 such stages might achieve a 90% U-235 assay but would have a very long equilibrium time.

The second method uses the stretched off-design mode, a method which requires that normal LEU production be suspended for a month or more. In normal operation, a typical diffusion stage enriches the feed in the product direction by approximately $\sqrt{\alpha}$. With a reduction in the product rate, this value can be made to approach the square of its normal value; when the increase in product enrichment is accumulated over many stages, the final enrichment is substantially enhanced at the expense of throughput. In practice, an assay of no more than about 50% U-235 is obtainable from natural uranium feed in this mode. The approach must be combined with a recycle of an intermediate product if higher assays are required.

The shortest path by which a proliferator could produce HEU from a civilian diffusion plant would result from using LEU from the plant product inventory for direct enrichment via stretched operation to an assay of up to 80% U-235. This scenario, essentially a two-stage enrichment of natural uranium, requires

more time as enrichment increases and the utilization of the feed is reduced. Table 3.1-4 shows the assays associated with equilibrium time.

Table 3.1-4. Products and Equilibrium Times for Stretched Operation of LEU Plants

Product Assay % U-235	Feed Assay % U-235	Tails Assay % U-235	Equilibrium Time (Months)
80	3.2	2.5	9
70	3.2	2.0	4
70	3.2	1.5	7
50	3.2	1.5	2
40	3.2	1.5	1

Whether and how either of the preceding approaches could be conducted without early detection is a function of the quality of the safeguards.

Dedicated Facility -- Gaseous diffusion cannot be excluded a priori as a technology for the military production of HEU, since gaseous-diffusion plants were first constructed for that purpose, and for over three decades, they have been the primary means for enrichment for weapons in Britain, France, People's Republic of China (China), Russia, and the United States. However, the effectiveness of gaseous diffusion depends on how thoroughly the detailed development of the diffusion barriers, UF_6 seals, and other critical components has been pursued. Given the availability of the centrifuge options, gaseous diffusion appears unlikely to be the technology chosen for a dedicated facility. Nevertheless, the possibility cannot be excluded that a simple crude process might be assembled by a country prepared to accept a relatively low U-235 assay.

Centrifuge

The centrifuge is implicitly a device with a small throughput and great operational flexibility. Depending on the intended HEU production rate, a dedicated facility would be configured either in a long cascade or in a

batch-recycle mode. Adaptation of a commercial facility could be made either by a series reconnection of the normally parallel cascades or by a batch-recycle operation. (With centrifuges, there is no need to resort to the less efficient stretched operation.)

Abuse of Civilian Facilities -- The technical opportunities for HEU production in a commercial centrifuge plant arise because the plant has numerous parallel cascades, each of low throughput. Small-scale production of HEU can be accomplished by a batch-recycle procedure that employs a fraction of the cascades. Alternatively, relatively straightforward series reconfiguration of the cascades would allow the production of 100 kg of HEU from natural uranium by using only 2% of the capacity of a 10^6 SWU/year plant for a year, the entire plant for a week. These times would be cut by a factor of about six if LEU replaced natural uranium as the feed. Table 3.1-5 displays information which is based on results of an analysis of a plant made up of a number of modular LEU cascades, each having 1600 SWU/year capacity. Note that the increment of plant capacity in Table 3.1.5 is only 30,000 SWU/year. The diversion of greater amounts of plant capacity would reduce the time required in inverse proportion.

Table 3.1-5. Times Associated with Abuse of a Commercial Centrifuge Plant (Capacity Diverted--30,000 SWU/year).

Relevant Times	Batch Recycle	Reconfigured Cascade
Time to modify plant	0	7 days
Time to produce 100 kg HEU from natural feed	286 days	142 days
Time to produce 100 kg HEU from LEU feed	41 days	32 days

The reliable detection of covert diversion requires a particularly sanguine view of the efficacy of safeguards.

Dedicated Facility -- There is a pervasive concern that a relatively simple centrifuge is a device upon which a lesser-developed country could base a nuclear-weapons capability. Centrifuge technology appropriate to uranium isotope separation was not classified until 1960, and there is no doubt that many countries have the design and construction skills to exploit the available data base and build at least a small number of experimental centrifuges. The technology exceeds the capability of car repair shops but not of jet-engine manufacturers. A development time of less than 10 years would be required for a completely independent program. The time would vary with the level of industrial capability of industrial countries.

However, with natural uranium feed, either about 10,000 elementary centrifuges, each of about 2 SWU/year capacity, or about 1000 intermediate centrifuges (such as those built by URENCO) would be needed to produce a hundred kilograms of HEU per year. All of these numbers would be reduced by a factor of four if 3% enriched feed were available. Moreover, development and construction of a 100 kg HEU/year plant would require 5 years and plant costs in excess of $100 million. If there were no trade in centrifuges, nations seeking a nuclear-weapons capability by this path must be capable of designing and manufacturing a large number of centrifuges. The likelihood that nations with less advanced nuclear programs might acquire a nuclear-weapons capability through centrifuge technology would be reduced by limiting international trade in centrifuges or critical components.

Aerodynamic Systems

The available modes for HEU production using an aerodynamic system like the Becker nozzle or the UCOR vortex tube are analogous to those available for the diffusion and centrifuge systems and include the development of long cascades, batch recycle, and stretched operation of LEU cascades. Because a commercial plant is expected to have very few parallel cascades (a plant made up of many small-unit cascades would be uneconomical and might be regarded as suspect), their rearrangement may not be feasible. The working fluid is 5% UF_6 in hydrogen for the Becker process and 1 to 2% UF_6 in hydrogen for the UCOR process.

Abuse of Civilian Facilities -- Since the inventory of an aerodynamic LEU plant is modest, batch recycle of the product is feasible. A stretched cascade operation is also feasible; as with gaseous diffusion, reducing the

product rate can produce an assay up to about 50% U-235 from natural feed at the expense of throughput. In a large, optimally designed plant, an assay of 70% can be obtained in a single pass starting with a 3% LEU feed. Since an aerodynamic enrichment plant will contain only one or a few cascades, a large segment of the plant must be removed from normal operation if HEU production is attempted.

If a large (5 million SWU/year) plant were seized, the production of 100 kg of 70% U-235 would take from 1 to 3 months, depending on whether stretched operation or batch recycle were employed.

Dedicated Facility -- The separation units of the Becker process contain extremely small nozzle/knife-edge configurations (with characteristic dimensions on the order of a tenth of a millimeter), compatible compressors, and process control elements. The basic technology is available from the open literature, and apparently straightforward techniques for making separators from a stack of thin photo-etched wafers manufactured in the same manner as printed circuit elements have now been described. An HEU plant is likely to employ a long cascade whose construction would be a substantial undertaking and would take years, employ hundreds of workers, and cost over $100 million. The existence of the considerable facility and its 10 to 50 MW power facilities would be difficult to conceal.

The Special Case of the Calutron

A calutron is capable of producing HEU enriched to about 90% in a single stage from LEU, but enrichment from natural uranium would likely require two stages. The unit cost of a calutron separator is so high that it is not a candidate for the civilian enrichment of reactor fuel uranium.

About 400 World War-II devices (with an ion current of 120 ma) would be required to separate 100 kg of HEU from a feed of 3% uranium at a 1978 cost in the vicinity of $200 million, and at least four to eight times as many would be needed if the feed were natural uranium. But advances in ion-source technology might substantially reduce the number of devices required, and the use of modern magnet technology could conceivably reduce the cost of each unit. Recent studies indicate that a system using LEU feed to produce 100 kg

of HEU might cost about $100 million. Signals that electromagnetic separation are under development on a substantial scale might therefore indicate the development of a moderately expensive enrichment "topping" capability. Any indication that the calutron is under large-scale development may raise suspicion since it is directly usable for HEU production and does not provide an economically feasible route to LEU.

Chemical Exchange

Analysis of chemical exchange technologies is not complete. Current indications are that HEU can be produced only very slowly. There is every indication that the production times will always exceed (maybe by a large margin) those of a gaseous-diffusion plant.

Atomic Vapor Laser Isotope Separation (AVLIS)

This subsection (with the two which follow) treats a process which is in such an early stage of development that it has not yet succeeded in producing substantial quantities of LEU. Hence, an assessment of its proliferation in the same detail as in other technologies is not possible. If laser isotope separation for LEU production proves feasible, specialized designs for HEU can quite likely be developed. But whether a plant configured for the civilian production of LEU can be adapted to produce HEU without substantially redesigning the plant is a matter of some controversy.

Abuse of Civilian Facilities -- The collector design now envisaged for a commercial LEU enrichment plant is designed to maximize LEU throughput and is incompatible with the production of HEU in a single step. Logically, then, any HEU production must depend either on conducting a multistep recycle operation or on rebuilding the system with a collector of the form which might be used in a dedicated plant. There are significant obstacles to the straightforward conduct of batch recycle. One involves the material hold-up in the uranium vapor sources (about 100 kg of feedstock for LEU production); at the very least, consideration of safety will make it necessary to replace or modify those sources with smaller sources in the later stages of recycle. Moreover, in these latter stages, the uranium evaporation rate must be reduced

to limit the quantity of U-235 to a level that can be handled by the available laser flux. One laboratory asserts that when additional difficulties associated with vapor dynamics at the collector are taken into account, batch recycle becomes so complex that a better approach is to rebuild the system for single-stage enrichment. If so, HEU production becomes a major venture involving perhaps several years of R&D to evolve the redesign and to implement a considerable system modification program. But once in operation, an AVLIS module would be able to produce 100 kg of 90% HEU in a little over a month.

HEU production in AVLIS will probably always be more difficult than batch recycle in a centrifuge plant. Whether the path of batch recycle for AVLIS is indeed as complicated as suggested by preliminary study is being re-examined.

Dedicated Facility -- Several laboratories have speculated on the characteristics of an HEU configuration for AVLIS. One believes that a batch-recycle operation will be extremely difficult to conduct; however, a single-stage enrichment from natural uranium to an assay of perhaps 40% U-235 should be feasible by using a specialized product extractor. Further enrichment would presumably be feasible with any of several forms of "topping" stages. For an AVLIS system to produce 50 kg of U-235 per year, a number of major components must be developed. These components include a vapor source capable of evaporating a kilogram of uranium per hour, a powerful multifrequency laser system which ionizes only the U-235 isotope, and, unless batch recycle proves feasible, a collector whose nonselective pickup of U-238 is only a few parts in a thousand. These components do not constitute a simple "table-top" system. One laboratory estimates the cost of such a plant at $50 million.

Molecular Laser Isotope Separation (MLIS)

Once MLIS is proven as a viable concept for producing LEU, the evolution of a primitive dedicated HEU facility appears straightforward and could be based on a multistep batch recycle of the product. Some reconfiguration of a commercial LEU plant would be required if it were to produce HEU.

Abuse of Civilian Facilities -- Without doubt HEU could be produced in a civilian MLIS plant by a batch-recycle process if the product collector were replaced by specialized versions tailored to the specific properties of the

batching sequence (especially the concentration of U-235 in the UF_6, which must be controlled to match the laser flux). Such an operation would require either interruption of the LEU production process or the nearly surgical removal of one of the very large separation stages of the plant. These activities would present considerable difficulties and would require an R&D and planning phase to mitigate them. The degree of difficulty and the duration of this preparatory stage are currently undergoing a critical reassessment. Present estimates are that modifying a plant after an overt diversion may take three to six months, after which HEU production would take little more than a week in a 9 million SWU plant.

Dedicated Facility -- An MLIS plant capable of producing 50 or 100 kg of HEU per year would be a moderate-sized structure containing a few large compressors capable of driving the expansion and supercooling of the UF_6-process gas stream before its photolysis by the powerful lasers. One laboratory estimates the capital cost of the structure to be nearly $100 million.

Plasma Separation Process (PSP)

It seems that the efficient management of large-scale plasma systems requires precise and delicate process control. Even when PSP is fully developed, it will surely be less straightforward to adapt to unconventional operation than a centrifuge plant. But there is no evidence that absolute technical barriers exist to the production of HEU.

Abuse of Civilian Facilities -- The requirements for the apparently complex batch-recycle operation of a PSP plant appear to make necessary a preparatory R&D phase lasting for a year or more to redesign the plasma sources and the process control. Recently, the possibility that such a development could be avoided by a straightforward modification of the collector followed by single-pass enrichment to HEU has been suggested by several laboratories. Present estimates are that if the single-pass operation proves feasible, 100 kg of HEU could be accumulated in a few weeks.

Dedicated Facility -- Two approaches to HEU production by using the PSP technology may be feasible. One is a single-pass operation using either a modified form of product collector or a biased operation of the current LEU

collector concept. The second is a batch recycle in which the successive plasma sources are tailored to the enrichment that prevails as they are used. The separation chamber has a volume on the order of 10 cubic meters, it uses a large and complex plasma source, and it requires a powerful superconducting magnet. One laboratory estimates the cost of a 50 kg HEU/year plant to be about $50 million. Clearly, this system is not a simple "table-top" system.

3.1.4 Summary and Conclusions on the Proliferation Implications of Enrichment Technologies

The first of three findings regarding enrichment technologies is that any enrichment technology may be used to produce HEU. But a degree of resistance even to overt diversion may be possible for some technologies because of the long time to produce HEU in a civilian plant (for gaseous diffusion or chemical exchange) or the difficulty in adapting the plant to HEU production (e.g., for some laser systems). Specific assessments are summarized in Table 3.1-6. Note that, contrary to earlier fears, the AIS technologies do not provide a simple "table-top" enrichment capability.

Second, safeguards that allow the IAEA to verify independently that no HEU is being produced and that LEU is not being diverted are in only the conceptual stage of development. It currently appears that for most systems, inspector access within the process perimeter may be a prerequisite for effective and timely safeguards operation. The level of intrusiveness appears least for gaseous-diffusion and (probably) chemical-exchange processes.

Third, any enrichment technology potentially can be used in a dedicated facility:

- Low- or intermediate-technology centrifuges place the means of producing HEU within the reach of moderately developed countries.
- The calutron provides a similar capability to a moderately developed country, but the cost is high. Indigenous development of aerodynamic systems requires less familiar skills.
- Costs do not drive the choice of technology. All of the above technologies cost on the order of $100 million for a 100 kg HEU/year plant, a significant, but not necessarily an absolute,

Table 3.1-6. Characteristics of Preparation and Production Stages of HEU Production in Civilian Enrichment Plants

Technology	Time/Resources to Plan and Develop Changes for HEU	Time/Effort to Install Changes	Time to Produce HEU	Comments
Gaseous diffusion	Weeks/low	Days/minor	Months to years	Basis is modified operation of whole cascade. Alternative is to introduce additional 300-stage "topping" cascade.
Centrifuge	Weeks/low	Days/minor	Days to months	Batch-recycle or cascade reconfiguration.
Aerodynamic systems	Weeks/low	Days/minor	Weeks to months	Basis for HEU production is 2-stage recycle of significant fraction of plant.
Chemical exchange	Weeks/low	Days/minor	Tentative conclusion is that time is in range months-to-years	Assessment still to be completed.
AVLIS	Probably substantial	Months/major	Weeks	These complex multidisciplinary processes are in early stages of development, and our perception of the difficulties of modification to HEU could be conservative. Concern is that short-cuts will appear in future.
MLIS	Probably substantial	Months/major	Days to weeks	
PSP	Probably substantial	Weeks/ moderate*	Weeks	

*If the single-pass operation were to prove feasible.

deterrent to many economies. Costs decrease if enriched LEU is available as feed (decrease by four times for centrifuge and calutron).

- The likelihood is low that any plant can be designed and constructed in a time less than several years.

- None of the AIS technologies appear to decrease substantially the difficulty of HEU enrichment. A concern is that still-to-be-discovered laser/material combinations may bypass the major technical barriers (uranium vapor sources or supercooled UF_6) of the present laser technologies.

- Detectability of a centrifuge or calutron development is influenced by diversion of industrial resources; that of laser technologies by diversion of R&D resources. Any import of key components increases detectability but reduces technical barriers.

Two major issues remain for resolution. First, it is still conceivable that the kinetics of chemical exchange impose a lower limit to the time required for HEU production, which is long enough to ensure that, with some institutional control, the technology is impracticable as a route to weapons.

Second, the means by which the AIS laser and plasma separation technologies can be adapted to HEU production are still poorly understood. The perception that adaptation is very difficult for AVLIS and presents significant difficulties for MLIS and PSP must be subjected to continued expert scrutiny.

3.2 PROBLEMS WITH SPENT FUEL: ITS STORAGE AND PLUTONIUM CONTENT

Projected accumulations of spent fuel and plutonium are based upon the available information on worldwide plans for nuclear power development. These plans reflect reasonably firm commitments through the 1980's but are subject to increasing levels of uncertainty thereafter, until 2000 or so, when only general trends merit discussion. However, under any reasonable assumptions for deployment schedules of different fuel cycles, the total amount of plutonium generated in the world until at least 2000 will not change much. Thus the importance of plutonium from a nonproliferation

viewpoint lies, instead, in its form and the quantity in which each form appears, its geographical dispersion, and the extent to which it can be controlled and safeguarded.

The discussion here deals with the problems presented for nonproliferation by these accumulations of spent fuel. These problems arise fundamentally, of course, because spent fuel is a particular form of plutonium which is not directly weapons-usable and is initially protected by high levels of radiation that decay with time.

Proliferation concerns for spent fuel in storage arise from the fact that spent-fuel accumulations will grow in quantity and in dispersed locations. The concerns stem from the following circumstances: spent fuel must be safeguarded against covert diversion, it is vulnerable to overt diversion, and it has radiation and chemical properties that may offer only limited deterrence to national proliferation.

The fact that large quantities of spent fuel will accumulate also results in pressures to alleviate the storage problem. In at least six nations--Austria, Belgium, Japan, Sweden, Switzerland, and West Germany--there are statutory requirements limiting the licensing of nuclear-power reactors to demonstrated progress toward solving the waste management problem. In some cases, this demonstration has been construed as a requirement for reprocessing. The problem that reprocessing creates is that plutonium in spent fuel which is not directly weapons-usable is transformed (with conventional PUREX reprocessing) into directly weapons-usable form. As the back end of the fuel cycle develops and as different processing techniques are used, so plutonium becomes distributed throughout the cycle in a variety of forms more or less easily modifiable to weapons-usable form. This problem is discussed in Section 3.3.

Safety and other matters of importance are not dealt with here. For the purposes of this discussion, however, it is assumed that spent fuel can be safely stored in storage ponds for many decades; that current cask designs permit transport of spent fuel after it has cooled for about six months; and that other forms of plutonium found in the fuel cycle can also be stored or transported safely, although the NRC has decided that when separated plutonium is transported in the U.S., it should be in the form of oxide and not nitrate.

3.2.1 Total Accumulations of Spent Fuel and Plutonium

Spent reactor fuel, mostly LEU fuel from LWR's, will be the primary source of plutonium through 2000. It has been projected that by that time, nations in the world outside the centrally-planned economies (excluding the U.S.) will have accumulated over 7000 GWe-years of reactor operation. If all these reactors were LWR's fueled with LEU, they would generate about 430,000 spent-fuel assemblies containing approximately 180,000 metric tons of heavy metal. (In the same period, the United States is expected to accumulate and store about 72,000 metric tons of heavy metal.) Of this heavy metal, about 1% will be plutonium. Of the 1800 metric tons of plutonium generated outside the United States, about 9% would be generated in 2000 itself. In other words, at the turn of the century, the inventory of spent fuel and its associated plutonium will be growing outside the United States at a rate of about 9% annually.

3.2.2 The Storage of Spent Fuel and Its Possible Removal from Storage and Transit

Even if all plans for reprocessing facilities through 2000 were realized, no more than about two thirds of the spent fuel expected to be generated outside the U.S. in the same period could be reprocessed, and at least one third, or about 60,000 metric tons, would remain in the form of spent fuel. Through the 1980's, most of this spent fuel can be expected to be stored in spent-fuel storage pools at reactors. Separated plutonium from spent fuel to be reprocessed, primarily in Europe and Japan but to some extent in Argentina, Brazil, and India, is planned for near-term use or for storage and later use in recycle or fast-breeder reactors.

Regardless of the fuel cycle, spent fuel will always be stored at reactor sites for a period of time to allow for cooling before it is shipped. As a result, significant quantities of spent fuel will always be stored under national control. Cumulative reprocessing capacity planned by Japan and some European nations (Belgium, Britain, France, Italy, and West Germany) may slightly exceed their spent-fuel discharges through the end of the century. However, the excess capacity is arguably smaller than the uncertainties involved in those plans. In any case, most nations will be faced with a significant spent-fuel storage problem.

These large accumulations create pressures to alleviate the storage problems. Even though planned and projected reprocessing capacity outside the centrally-planned economies is far in excess of projected recycle or fast-breeder needs, its effect on total spent-fuel accumulations through 2000 would be slight. If the nations with reprocessing plants collectively reprocessed their spent fuel through 2000 and used their excess capacity to reprocess the spent fuel from other countries, they could reduce the remaining spent fuel by only about 20%. With about 60,000 metric tons remaining, the demands for additional storage capacity will grow. Although many nations plan to increase pool storage capacity by compaction, and a number of these countries either plan or are considering away-from-reactor (AFR) storage facilities, most nations do not consider these facilities to be alternatives to reprocessing but necessities reflecting the demand for more storage space before reprocessing services can be provided. With a high degree of compaction and with maximum shuffling of fuel among reactors, at-reactor (AR) pool storage would be sufficient through the early 1990's for some nations and past 2000 for a few others. Since these conditions are implausible, however, commitments to alternatives to relieve pressures for reprocessing or AFR storage under national control in these countries will be needed in the early-to-mid-1980's.

Suggested variations in the difficulty of removal from the AR and AFR interim storage concepts are not great. Removal from pool-storage facilities appears to require slightly more effort than that from dry-storage facilities because the fuel-handling operations are somewhat more complex and time-consuming, and because the fuel assemblies must be encapsulated before shipment. Generally, however, fewer than five people are required to perform the removal, and the necessary equipment, except possibly the transport vehicles and casks themselves, is likely to be readily available at the facility. It is unlikely that removal of a threshold amount of fissile material would take more than a few days from the AR and conceptual AFR interim-storage facilities. Removal from geologic disposal facilities operating to permit retrieval requires a degree of effort similar to that for removal from a surface facility. Removal from such facilities operating to deny retrieval requires a much greater effort. For any type of facility, however, it is likely that specific features that would increase to some extent the times and resources necessary for diversion and would facilitate the application of effective safeguards could be incorporated at the stage of detailed design.

The diversion of spent fuel is perhaps easiest when it is in transit. Diversion from truck transport is far easier than diversion from rail transport since the rail casks weigh about 100 tons each. If near-real-time monitoring of shipments is not utilized, it might be possible for a nation to conceal the diversion of fuel by simultaneously shipping numerous fuel elements between

reactors and between storage areas. Verification of diversion could take weeks if the nation did not cooperate with the inspectors. Substitution of dummy fuel elements may also be possible.

3.2.3 Radiation Considerations in Storage, Transit, and Reprocessing

The radiation level from spent fuel decreases rapidly during the first year outside the reactor core, as several short-lived isotopes decay. After that, the decay is much slower, with tens of years being required to reduce the radiation level to one tenth this end-of-a-year level.

During the initial cool-down period of up to six months after removal from the reactor core, the radiation and heat present relatively formidable problems. Commercial shipping casks designed for longer cooling times may not offer sufficient heat-removal equipment or radiation protection unless radiation standards are relaxed.

To a nation, the radiation associated with spent fuel is not an insurmountable barrier to the removal or processing of spent fuel, particularly after it has cooled for about 6 months. During removal, transportation, and reprocessing, however, heavy shielding is required, and competent personnel would be needed to design and operate the reprocessing plant for extracting plutonium.

The radiation can be expected to increase the likelihood of time-consuming delays when problems do occur. However, at the national level, more time and money during design, construction, and testing, and for redundant design features of a clandestine reprocessing facility can help to overcome a lack of experience. This additional time attributable to the presence of radiation obviously increases the time during which detection could occur. During reprocessing operations, the fission products in the spent fuel may provide opportunities for detecting or verifying the operation of a clandestine facility. To most subnational groups, the radiation levels associated with spent fuel would present a formidable barrier.

Equipment used at the front end of the reprocessing plant would require cooling. The control of large quantities of iodine-131(I-131) gas, with its eight-day half-life, usually presents major problems to processing plant designers and operators, especially during the first few months after fuel is discharged from the core of a reactor. In summary, the radiation barrier is potentially a significant source of problems and possibly time-consuming delays during the initial six-month cool-down period. After this initial cooling period, the impact of the radiation barrier on proliferation activities may be in the nature of a threshold, one above which the radiation level requires the use of remote operations.

For a national campaign to extract 100 kg of plutonium or more from spent fuel, the radiation level at which a proliferator would probably use a fully remote operation, as opposed to shadow shielding, would range from tens to a hundred rem/hr at one meter from unshielded fuel. For spent fuel cooled beyond the point at which fully remote operations are required, shadow shielding with lead bricks and other special techniques can be employed to minimize doses. Individual LWR assemblies maintain a dose rate about 50 rem per hour or greater at one meter for 150 to 200 years. HWR assemblies, which are smaller and have less burnup, maintain this or a higher radiation level for about 70 years. Once operations become remote, the major impact of variations in radiation level or cooling time is to vary the required thickness of radiation shields. These variations are not considered significant. The effect of radiation during this period, that is, the requirement for remote operation, is not thought to be an insurmountable barrier at the national level but is a substantial impediment at the subnational level.

3.2.4 Safeguarding Spent Fuel in Storage and Transit

The safeguards approach for a spent-fuel storage facility is based on material accountability, containment, and surveillance. Accountability of spent-fuel assemblies includes correlating spent-fuel receiving rates with the amount of fuel in a storage pool and other material balance areas, and item accounting and possibly NDA methods for verifying pool inventory. Containment and surveillance are used to protect against tampering with measurements made for accountability, to ensure the validity of previous inventories or measurements by inspectors, and to ensure that a sudden diversion has not occurred. The effectiveness of the safeguards system as currently utilized is entirely dependent on the activities of the inspector.

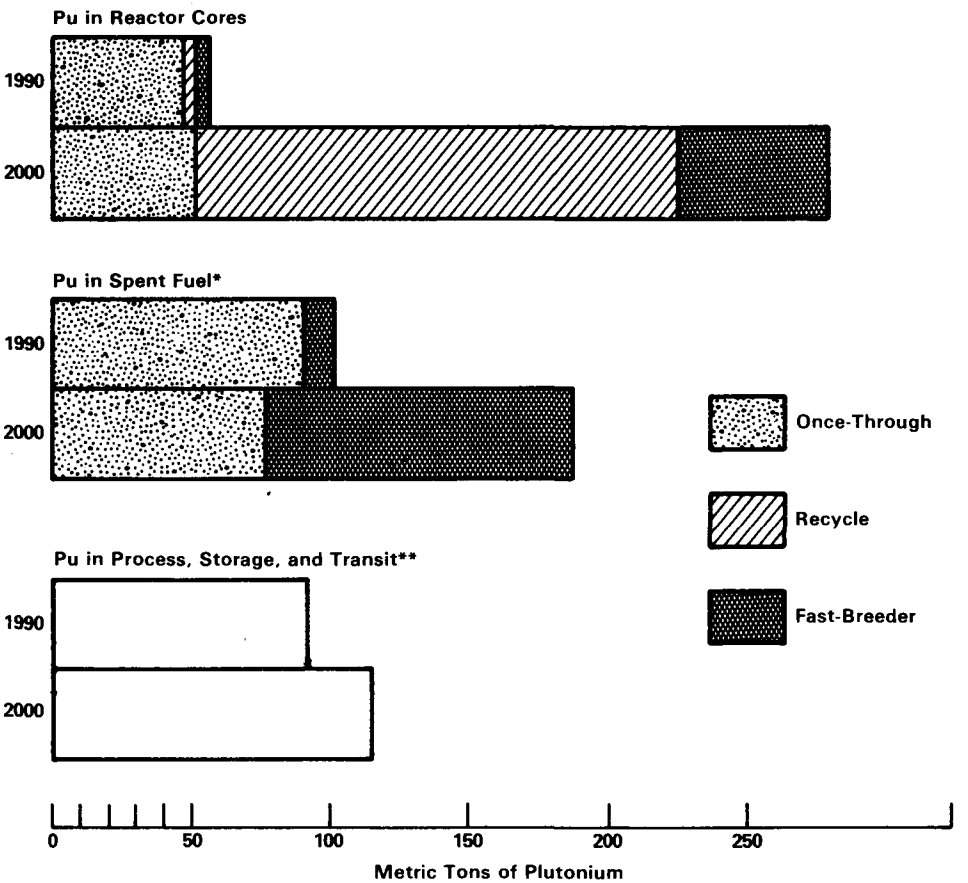
Material accounting of spent-fuel elements is in general more accurate than of bulk materials because of the discrete nature of fuel elements. However, some reactor operators disassemble fuel elements to replace damaged fuel pins, a practice which may increase in the future and make item accounting more difficult.

Since material accounting of spent fuel in transit from one facility to another can be complicated if the number of shipments is large or if the shipping time is long, international arrangements for transportation and storage of spent fuel and for accountability at disposal sites require further evaluation. Near-real-time tamper-indicating remote surveillance of spent fuel in transit and in storage is technically feasible and would appear to provide a substantially improved and effective safeguards capability for spent fuel.

3.2.5 Spent Fuel and Reprocessing

With accumulations of spent fuel increasing pressures to dispose of it somehow, some nations are considering reprocessing as one way to manage the problem. Some are considering moving to reprocessing for use in recycle and FBR reactors. Some have suggested that this may be an effective way to manage plutonium from a nonproliferation viewpoint by arguing that it is relatively inaccessible in the core while the reactor is operating. Regardless of the merits of this argument, the reprocessing and refabrication of plutonium can result in the widespread presence of plutonium in forms that are either weapons-usable or can be easily modified to be so.

The distribution of plutonium inventories throughout various segments of the fuel cycle as nations recycle MOX in LWR's and start-up FBR's is illustrated in Figure 3.2-1. This illustration assumes that LWR, reprocessing, and FBR plants are realized concurrently at rates similar to those projected by a group comprising only Japan and West Germany, and that the excess plutonium from reprocessing plants is used to start up and maintain about 3 GWe of plutonium-fueled LWR's per year between 1990 and 2000. This output represents about one half of the planned new reactors in this period. Thus, some LWR's would be using LEU fuel only, others recycle plutonium fuel, with some FBR's coming on line. The amount shown in spent fuel would represent the stockpile of spent fuel that is in excess of planned LWR and FBR reprocessing capacity. This stockpile could be reprocessed in the nations of the group if additional



* Assumes no reprocessing of FBR Fuel before Year 2000.
** 22 MT of Separated Pu Must be Obtained Elsewhere in Year 2000 due to Insufficient In-Group Reprocessing Capacity.
*** Based on Projections of a Group Combination Similar to Japan and West Germany Which Uses In-Group Capabilities Only and Uses Surplus Plutonium to Add 3 GWe Yr of Recycle Capacity Starting in 1990.

Figure 3.2-1 Plutonium Inventories at Various Points in a System Operating Both LWR's (Some Once-Through, Some Recycle) and FBR's***

reprocessing capacity were added, or it could be reprocessed elsewhere. The separated plutonium stockpile from in-group reprocessing would be used for startup of both FBR's and plutonium-fueled LWR's, for refueling FBR's, and for makeup fuel for the LWR's.

The plutonium would end up in the reactors, their respective fuel cycles, and in the FBR spent fuel being stored until FBR reprocessing comes on line. In short, the amount of plutonium in the form of fresh fuel or of in-process materials increases as nations make the transition from once-through to recycle or fast-breeder reactors. At least one half of the total fuel-cycle inventory of plutonium compounds would be out of the reactor during the transition period. Since the technical barriers to proliferation are not significant when plutonium is in bulk feedstock materials, effective international safeguards will be required for such materials if the nuclear fuel cycle proceeds toward recycle and breeder systems in the future.

3.3 REPROCESSING AND REFABRICATION FACILITIES

3.3.1 Introduction

In a reprocessing facility, uranium and plutonium are separated from the spent fuel discharged from reactors. In civilian fuel cycles, the separated uranium and plutonium are converted to forms suitable for storage or transport prior to refabrication into fresh-fuel elements. PUREX, the only commercially developed reprocessing system, results in complete separation of plutonium into a form that is weapons-usable.

The proliferation concerns about reprocessing and refabrication facilities are that:

- An in-system facility is provided that produces weapons-usable material.
- Plutonium can be removed from reprocessing and refabrication facilities in weapons-usable form and in forms that are relatively easy to modify.

- o This removal may follow abrogration or withdrawal from safeguards if they are in force or could be attempted covertly despite the safeguards system.

- o The capability is enhanced to construct out-of-system facilities for weapons purposes.

A central question to be answered is whether reprocessing inevitably provides easy access to weapons-usable material. This section examines briefly whether this situation can be altered either by the use of different processes or by the incorporation of engineering features in the facility. To assess whether this situation can be effectively altered makes it necessary to ask how easy it would be to modify new processes and facilities to produce weapons-usable material. In addition, the materials which are available in these commercial facilities would, if removed, require some processing before being weapons-usable either as metal or as oxide. These conversions and the out-of-system facilities required are also discussed here. The processes used to refabricate plutonium into new fuel elements obviously depend on the form of the product of the preceding reprocessing facility. Accordingly, both types of facilities and their processes are examined here.

3.3.2 Reprocessing

Basic Separation Processes

The PUREX process is the most widely known and used method of separating plutonium. It represents the culmination of U.S. efforts after World War II to develop the most efficient way of obtaining the purest possible plutonium for its military program. In fact, reprocessing of uranium-based nuclear-reactor fuel was first utilized about 35 years ago to separate the plutonium for one of the first U.S. nuclear weapons. Since only a minute part of the material processed was plutonium, stringent requirements were placed on the chemistry utilized. It was necessary to purify the plutonium by removing even traces of light elements and fission products so that the product material was usable in a military weapon and had a minimum amount of radioactivity. Under the pressures of World War II, a reprocessing plant (the first of a kind) was designed, built, and successfully operated in less than 18 months.

One of the process criteria for the weapons program emphasized obtaining very pure material so that radiation levels would be low. Early methods did not recover the uranium, minimize the high-level waste volume, or minimize the release of gaseous fission products. Nuclear-weapons stockpiling programs provided the incentive to develop better and more efficient techniques for removing plutonium from the irradiated fuel and to reduce the materials required for the total process. These developments resulted in the PUREX process.

With the prospects of a large civilian nuclear-power program, the incentive to minimize the life-cycle costs of the power has been an additional driving force for maximizing the economic utilization of fuel-cycle materials. This incentive has spurred the continued development of reprocessing technology as a potential contributor to this goal.

Although the nuclear-power fuel to be reprocessed is different--burnup ten times or more greater, oxide instead of metal is used, and zircalloy instead of aluminum clad is used--the PUREX process was readily adapted to commercial purposes. It appeared to minimize the financial or technical risk of expanding to a commercial scale and also promised the lowest cost. Accordingly, the commercial plants that have been designed for use today have been based on this process.

PUREX-based technology has spread to other nations although the U.S. has not permitted the sale of reprocessing facilities. Numerous training programs have been used to export the technology, however.

The PUREX process uses solvent extraction for a very high degree of separation of uranium and plutonium from fission products and, as implemented, produces pure separate streams of plutonium and uranium in the form of nitrates. The process generally involves cutting fuel elements into small pieces (1 to 3 inches long) prior to dissolution in nitric acid. The fuel is dissolved out of the clad. The spent-fuel cladding and end fittings, or hulls, are then compacted and treated for disposal. The hulls are radioactive and contaminated with uranium, plutonium, and fission products. Vault storage is utilized for the plutonium oxide until it is transferred to fuel fabrication.

The reprocessing of thorium-based nuclear fuels is a somewhat less developed technology than is PUREX, although hundreds of tons of thorium have been processed in government facilities using the Thorex process. The principles are well understood because the Thorex separation process is similar to PUREX. The recovery of plutonium from denatured uranium-thorium fuels would introduce new uranium-plutonium separation techniques, but the commercial development required could probably be based on existing techniques. There are several differences between reprocessing thorium-uranium-plutonium fuel and reprocessing uranium-based fuel.

- Thorium is less soluble in nitric acid than is uranium.
- The U-233 produced may contain significant quantities of U-232, the decay products of which emit gamma-ray radiation. The conversion equipment and fuel-fabrication processes require greater shielding and may require remote operation.
- The separation of thorium fuels is more difficult to control; the formation of solids with solvent degradation products is more likely.
- The throughput for a given facility is less for the Thorex than for the PUREX process (larger equipment is required for the same uranium fuel throughput).

The oxide-conversion step for the U-233 product might be a modified coprecipitation process with remote fabrication required for U-233 fuels.

The proliferation vulnerabilities of reprocessing of thorium-uranium (U-233)-plutonium fuels are not significantly different from uranium-plutonium fuels; that is, highly purified streams of weapons-usable materials are available. While U-233 may be isotopically denatured, plutonium would still potentially be available. An option not to separate the plutonium, that is, leaving the plutonium unseparated in the fission-product waste stream, would shift safeguards concerns from spent fuel to nuclear waste. Modification of the reprocessing facility to separate plutonium would not be formidable, however.

Alternative Separation Processes

Many different processing schemes have been demonstrated at the laboratory level (see Table 3.3-1) and have been described in the open literature; some are easier and more economical to commercialize than others. The basic steps in reprocessing involve dissolution of the fuel elements and separation of uranium and plutonium. The fission products may be separated first (PUREX, REDOX) or uranium may be separated (fluoride volatility, ion exchange) or the plutonium may be separated (bismuth phosphate).

There are several processes, some aqueous, some nonaqueous, that can be used to perform separations: solvent extraction, ion exchange, volatility-absorption, and precipitation. In all cases, the process chemistry is controlled by factors which include mass flow, temperature, and solvent/acid concentrations although aqueous processes apparently show a higher degree of flexibility than nonaqueous ones. All of the processes which have been investigated on a laboratory scale, with the possible exception of the pyro-processes discussed below, are capable of separating fission products (decontamination) so that there is less than one part in 10^5 of fission products remaining with the product. Also, the chemical separation factors for uranium and plutonium are relatively high; that is, in most cases separation of uranium compounds from plutonium compounds is easy to perform, with less than one part in a hundred remaining in the product. Some experienced reprocessing engineers believe that processes that only partially separate uranium or fission products from plutonium can be readily modified to obtain separated plutonium by staging, by material recycling, or by modifying the process control variables.

The certainty with which this analysis can be supported varies, of course, with the current state of knowledge regarding specific processes, and it should be noted that none of the nonaqueous processes have been developed to a plant-design stage. Because substantial technological development is required, it would appear that these processes could be considered for application only to alternate fast-breeder fuel cycles using metal instead of oxide fuels. Some of these processes, however, like pyrometallurgy, have potentially interesting features for proliferation resistance and have received preliminary analysis. Most, but not all, of the process steps have been demonstrated on either a laboratory or a pilot-plant scale. In the zinc distillation process, the normal product would be a uranium and plutonium alloy contaminated with fission products yielding estimated radiation levels

Table 3.3-1. Reprocessing Schemes for Oxide Fuels

PROCESS	BASIC STEPS	STATUS	COMMENTS
BISMUTH PHOSPHATE	Head end, dissolve in nitric acid, precipitate with bismuth phosphate	First process used in weapons program	Uranium goes with fission products
REDOX	Head end, dissolve with nitric acid, separate fission products, solvent extraction, partitioning with hexone	Second process used in weapons program	Produces purer material, large volume of waste
PUREX	Head end, dissolve with nitric acid, separation of fission products by solvent extraction, partitioning of U and Pu by using tributyl phosphate	Third process used in weapons program. Has also been operated commercially	Requires cooling of fuel to prevent solvent degradation
THOREX	Similar to PUREX except used to reprocess thorium fuels	Has been operated commercially	Requires higher-volume process equipment
FLUORIDE VOLATILITY	Convert U to UF_6 by acid and fluorine. Pu goes with fission products	Demonstrated in lab	Very corrosive process, must keep moisture out of system
ION EXCHANGE	Head end, dissolve with nitric acid, cation or anion exchange	Demonstrated in lab	Radiation damage of resins requires longer cooling times, 5% uranium loss
PYRO-PROCESSING	Head end, convert to metal, melt, salt extraction, solidify, melt, cast	Demonstrated in lab	Produces metals, instead of oxides

of about five hundred rems per hour at one meter. Both process and equipment modifications would be required to yield a plutonium stream which would still be contaminated to a level of about ten rems per hour at one meter. If these changes were planned for and components were pretested covertly, it is estimated that several months would be required to effect them after the facility had been seized. It would be quicker to recover the plutonium in a dedicated facility which would take a year or more to prepare covertly.

Alternative Reprocessing Schemes

Alternative reprocessing schemes fall into three classes:

- Those in which plutonium compounds are never separated from uranium.
- Those in which there is a radiation barrier with the uranium and plutonium compounds (i.e., the fission products are not totally separated) or in which a radioactive spikant is added.
- Those in which the facility design is engineered to reduce access to plutonium or to inhibit process modification and enhance safeguards.

Dilution with uranium may be effected either by coprocessing or co-conversion. Radioactive contamination may be effected by either spiking or partial decontamination (alternatively, a radiation barrier could be introduced by preirradiating the fuel). Other technical measures include passive engineered features to reduce accessibility, active denial features, and perhaps integral separation and fabrication facilities. To obtain pure plutonium would require changes in some cases to the process itself, in some cases to the process equipment, in some cases to the facility, and in some cases to all three. The activities required in cases where changes in the chemical process are involved can be characterized by the times and efforts needed to prepare for the changes and to carry them out. These times and efforts are summarized in Table 3.3-2.

The overall proliferation resistance of a number of such alternatives in terms of the removal of material, the misuse of a reprocessing or refabrication facility, and the conversion in dedicated facilities required to obtain

Table 3.3-2. Characteristics of Activities Required for Plutonium Production from Different Separation and Reprocessing Schemes*

Technology	Time/Resources to Plan and Develop Changes for Pure Pu	Time/Effort to Install Changes	Time to Produce Pure Pu	Comments
Normal PUREX	None	None	None	Standard process
Co-conversion	None	None	None	Separated Pu is present in the process
Coprocessing	Weeks/low	Days/minor	Days	
Partial decontamination	Weeks/low	Days/minor	Days	
Spiking	Little or none	Little or none	Little or none	
Pyrometallurgy (zinc distillation)	Months/substantial	Months/major	Weeks	Process requires substantial technology development

*All schemes except the last listed in the table are based on the aqueous PUREX process and could be used to produce variations of the oxide fuels of the reference recycle and breeder fuel cycles. The pyrometallurgy process would be used for metallic fuels, depends on technology to be developed, and would probably be considered for application only to alternative fast breeders.

plutonium metal is discussed in Section 2.2.3. The results are summarized in Table 2.2-1 of that section.

3.3.3 Plutonium Conversion and Mixed-Oxide Fuel Fabrication

After separation of fission products in the reference PUREX process, the conversion of liquid uranium and plutonium nitrates to oxides must be performed before the fabrication of fuel elements. There are several processes which can be utilized for this conversion (see Table 3.3-3). The alternative reprocessing schemes just described generate different products and therefore require different conversion processes. Since some of these conversion processes may at the same time provide some separation of spikants, fission products, or uranium from the plutonium, special care must be used to match the conversion process to the reprocessing product stream so that the desired proliferation resistance, if any, is retained. These relationships are indicated in the table. Moreover, precisely because some conversion processes can separate spikants, fission products, and uranium from plutonium, the proliferation implications of this process step are similar to those of reprocessing. The uranium and plutonium oxides are appropriately blended during the conversion process or afterwards to the desired ratio, that is, about 5% PuO_2 for recycle in LWR's and 15 to 25% PuO_2 for fast-breeder designs. In the reference case, the blending is achieved by the mechanical mixing of the oxide powders after conversion. In coprocessing, the appropriate mix is achieved before conversion.

The blended materials are then pressed to form a pellet, and fired (sintered) at about 1200°C. The pellets are mechanically assembled into fuel rods. To recover fissile material from the MOX fuel, the pellets must be removed from the clad and dissolved in acid. Some processes have been developed to improve the dissolution characteristics of MOX. The Coprecal process was developed so that fuel-fabrication plants could prepare MOX that was readily dissolvable (as scrap or as spent fuel) in nitric acid for recycling of fissile fuel.

Table 3.3-3. Plutonium Conversion Processes (Nitrate Solution to Oxide)

Type	Advantages	Disadvantages
Peroxide Precipitation	No reductant needed, very high decontamination; H_2O_2 only reagent	Potential explosions; long digestion times; low-density product; moderate losses (need recycling); not useful for coprocessing or prespiked material
Pu(IV) Oxalate Precipitation	High-stability solids and solutions, high decontamination; good in batch and continuous processes	Careful control of process required numerous reagents; high losses (needs recycling); not useful for coprocessed or prespiked material
Pu(III) Oxalate Precipitation	Rapid settling, easily filtered, noncritical conditions, low losses, good impurity separation	Not so much experience as with Pu(IV); not useful for coprocessed or prespiked material
Direct Denitration	No added reagents; simple equipment; useful for coprocessed or prespiked material	Unproven technology mechanical problems; no decontamination (an advantage for prespiked material)
Sol-Gel Process	Adaptable to coprocessing; high-density beads produced directly (remote handling of spiked material may be feasible in Sol-Gel equipment)	Complex process; elaborate equipment; needs testing; requires good control; no decontamination (an advantage for prespiked material). Density of sphere-pak fuel lower than pellet fuel.
Coprecal Process (ammonia coprecipitation and fluidized-bed calcination process)	Good for coprocessed material. May be adaptable to spiked material. Developed to improve dissolvability of MOX fuels. Cannot be used if PuO_2 > 40%.	No large-scale proof of feasibility yet; no decontamination (an advantage for prespiked material)

3.3.4 Alternative Forms of Plutonium

The previous discussion has emphasized that plutonium in different forms occurs at different points in the fuel cycle. Table 3.3-4 provides a qualitative scale, from G to A in order of increasing sensitivity, for judging the relative sensitivities according to the different forms of plutonium. The table gives the alternative forms in which plutonium exists at different points in the reference recycle system, which includes PUREX reprocessing. The forms are listed in decreasing order of inherent protection, that is, in decreasing order of the amount of processing required to obtain weapons-usable material. The key proliferation activities required to obtain weapons-usable material from fuel-cycle material includes preparation, acquisition of material, and processing of material. The elaboration of this table in terms of the resources and times required and of considerations relevant to detectability are taken up next in Section 3.3.5. Table 3.3-4 also notes the approximate amounts needed of each form of plutonium to yield 10 kg of separated plutonium and related handling difficulties.

The effects of the alternative processes on the form of plutonium available in the fuel cycle influences the entries in the table. For example, the effect of co-conversion is to eliminate pure PuO_2 (Level B) everywhere in the cycle. The level of protection in the reprocessing plant would be further increased by coprocessing which would eliminate Level C. Pre-irradiation would increase the protection of fuel assemblies from Level E to Level F.

3.3.5 Dedicated Processing Facilities

Dedicated processing facilities are out-of-system facilities that are part of a military nuclear fuel-cycle system. This section describes typical chemical facilities that would be capable of processing spent fuel, fresh fuel, or intermediate fuel-cycle materials into metallic weapons-usable material.

Dedicated processing facilities would differ significantly from commercial fuel-cycle facilities in that economic, environmental, and long-term operating considerations would not dominate the design. One major design objective would be to remain undetected, especially during facility construction and prestartup testing. The operating scale of such a facility would be similar

Table 3.3-4. Alternative Forms of Plutonium at Different Points in the Reference Recycle System

Level of Protection	Material	Location in fuel cycle (including transportation between facilities)	Processing Necessary	Approx. mass needed for 10 kg of Pu (arbitrary)	Other difficulties
G	Fuel assembly during irradiation	Within reactor core	Shut down of reactor, removal and cooling, the mechanical and chemical separation followed by conversion	1000 kg (2 PWR sub-assemblies)	Intensely radioactive
F	Discharged irradiated fuel subassembly	Reactor storage ponds, interim storage, reprocessing plant, long-term storage	Mechanical and chemical separation followed by conversion	1000 kg (2 PWR sub-assemblies)	Intense radio-activity falling with time after discharge
E	Fuel sub-assembly (prior to irradiation)	Recycle fuel-fabrication plant, reactor site	Mechanical and chemical separation followed by conversion	140 kg (1 PWR sub-assembly) 50 kg (1 LMFBR sub-assembly)	Toxicity Radioactivity*
D	Mixed Oxide $(Pu+U)O_2$	Recycle fuel-fabrication plant (possibly reprocessing plant)	Dissolution and separation followed by reduction to metal	140 kg (PWR fuel) 50 kg (LMFBR fuel)	Toxicity Radioactivity*
C	Nitrate $Pu(NO_3)_4$	Reprocessing plant	Conversion to oxide followed by reduction	17 kg	Toxicity Radioactivity*
B	Oxide PuO_2	Reprocessing plant, plutonium storage site, recycle fuel-fabrication plant	Reduction to metal and fabrication	12 kg	Toxicity Radioactivity*
A	Pu metal	Not in reference recycle system**	Fabrication only	10 kg	Toxicity Radioactivity*

*Depends on the plutonium isotopic composition
**Can be present in other civilian nuclear activities, like, for example, critical facilities

to chemical pilot-plant equipment. The most extensive facilities would be required for processing spent fuel; the complexity is reduced successively for spiked fuel materials, for fresh fuel, for MOX powder, and for PuO_2. The product of the dedicated facilities is plutonium metal; other facilities needed to convert the buttons into weapon shapes or to prepare nonnuclear weapon components are not discussed here, but such facilities would, of course, also be built and sited for maximum secrecy.

Dedicated Facility Design Guidelines

Guidelines permitting comparisons of dedicated processing facilities are required for the estimates of the resources required, the times required, and detectability to be as consistent as possible:

- Plant capacity should be sized to produce about 10 kg of plutonium as soon as reasonably possible once material was removed from the fuel cycle; 100 kg should be obtained expeditiously.
- Plant capacity need not recover more than about 100 kg of plutonium in one year for covert scenarios.
- Plant should be sited to minimize detection during construction; possible options are within military reservations, within other chemical plants, or within an aircraft hanger or warehouse.
- Plant facilities should emphasize a high probability of success and simple, reliable operation.
- No special environmental regulations need be met; however, personnel exposure rates of up to 50 rem/yr can be assumed.
- Product recovery rates can be much lower than in industrial facilities (e.g., 85%), and liquid and solid wastes can be stored on-site.

Typical features of dedicated facilities for converting fuel-cycle materials into weapons-usable material are shown in Table 3.3-5. Specific details would depend on the material form in the fuel cycle, the chemical training available to the personnel directing the program, and the conditions which exist in the nation of concern. Thus, there are major uncertainties in the estimates of resources and times required for dedicated facilities. These

Table 3.3-5. Features of Dedicated Processing Facilities for Processing Spent Fuel

Feature	Purpose and Effort
1. Siting of plant as an adjunct to an existing chemical plant or laboratory.	Construction is less obvious than at a new site. Services (utilities, laboratories) are not required.
2. Process Selection Examples	
a. Transport of spent fuel would be accomplished in a fuel-assembly truck cask built in the country.	Smaller capacity cask is more maneuverable and less detectable.
b. Size reduction of spent fuel rods would be performed with abrasive saw in water pools.	Less obvious than a specialized rod-shearing device.
c. Ion exchange would be used to recover plutonium rather than solvent extraction system if feasible.	Ion exchange systems more generally used in chemical operations. Tributyl phosphate solvent would not be required.
d. Liquid wastes from operation would be neutralized and stored in underground vault or steel tanks.	Acid waste requires special stainless steel; waste solidification is not required.
e. Mirrors and TV cameras used for remote viewing of operations.	Manipulators and shielding windows might be traceable.
f. Precipitation processes could be considered for Pu separation if personnel were inexperienced in ion exchange systems.	Pu oxalate, Pu fluoride or Bi-phosphate system separates Pu from uranium, but more fission-product removal requires multiple cycles, more wastes.
3. Batch processes with high yield but provisions for problems made by including multiple lines and spares.	Minimum dependence on skill and experience of personnel.
4. Few process samples would be taken to reduce product losses, confirm proper chemical additions but not to establish close accountability.	Not concerned about achieving high yield in reactions or in recovering all the material but avoid major plant delays (criticality accident, fire, etc.).
5. Use hands-on operation, shadow shielding, and tongs for radiation levels up to tens of rem/hr.	Reduce problems and facilities requirements associated with remote operations, sophisticated equipment.

uncertainties stem from such considerations as (a) a choice of different chemical techniques (e.g., some might select ion exchange to separate materials while others might select solvent extraction), (b) variations in feed material composition (e.g., plutonium in spent fuel varies with exposure and reactor design), (c) the interdependence of cost and time, and (d) specific conditions in a nation. In addition, specific difficulties in operating dedicated facilities affect these estimates. Some specific difficulties are given in Table 3.3-6. Most importantly, there exists little or no comparable experience to serve as a basis for making these estimates. They are the collective informed judgment of experienced professionals in the chemical reprocessing field.

The estimates of resources and time associated with dedicated facilities for misuse of fuel-cycle materials are summarized in Table 3.3-7. The estimates are reported as ranges rather than single values but cannot accurately reflect the range of the uncertainties just cited. The analysis was made by taking a consistent approach for reliability and competence of design while allowing for typical minor problems in new facilities. The lower end of the range does not represent a minimum time or cost, nor does the upper end allow for incompetence. Specifically, a range of 1 to 3 weeks is estimated to produce 10 kg of plutonium from spent fuel. If LWR fuel remains in the reactor for its designed lifetime, then 1 year after it is discharged, processing it was estimated to require about 12 days to recover 10 kg of plutonium metal; with minimum delays, the time could be 8 days. If the design were poor, if equipment were shoddy or makeshift, or if the operational personnel made poor decisions, many weeks could elapse. Similar factors affect development time (design, procurement, facility construction, and cold testing). Specific factors associated with the industrial base present in the nation might affect vessel fabrication or instrumentation and piping deliveries (either longer or shorter than in the U. S.). However, modifying existing facilities could shorten the construction effort (but might extend operating time). System checkout time would depend on the program management and the results in checkout of individual equipment subsystems. The time to recover 100 kg of plutonium would be dependent on the operating performance of the equipment; about 50% availability is considered likely for a system built when great speed is urgent. Estimates of the time to build and prepare to operate facilities to process spent fuel range from 12 to 24 months (versus a wider range of 4 to 30 months reported by the General Accounting Office). For dedicated facilities, much of this range may be associated with different assumptions on quality of equipment, operating lifetime, and personnel risk, used by different analysts. In general, there is little agreement among United States engineers on the variation in these estimates when applied to other countries and to engineers with a potential wide variation in experience and training. The times might be a little shorter if several experienced staff were directing the effort; however, the times could be significantly

Table 3.3-6. Difficulties in Operation of Dedicated Facilities for Spent Fuel

PROCESS STEP	DIFFICULTY	CONSIDERATION TO OVERCOME DIFFICULTY
1. Move spent fuel from storage site, receive and unload at dedicated facility.	Mechanical equipment problems; damage to fuel in transit	Spent-fuel handing in reactor basins is routine work. Cask handling is routine. Special casks may be less restrictive. Practice using cold fuel
2. Cut fuel (abrasive sawing).	Equipment failure; poor visibility in basin	Spare equipment. Provide filter and water circulation in basin. Practice using simulated fuel
3. Transfer cut fuel to dissolver.	Mechanical problems, contamination	Practice using simulated fuel
4. Dissolve fuel.	Acid too hot or too concentrated; solution spills	Accepted contamination. Provide sump; pump to waste. Enlarge dissolver
5. Filter or centrifuge dissolver solution.	Filter clogs or centrifuge fails	Replace, backwash, or by-pass equipment. Solids no problem in solvent extraction; solids can eventually plug ion exchange columns
6. Feed to ion exchange or solvent extraction.	Poor control of hydraulics, poor separation	Adequate instrumentation proven in cold runs
7. Precipitate PuF_3, collect, wash, dry.	Excess losses if chemistry not correct	Process is published
8. Reduce PuF_3 to Pu, clean up, pickle.	Impure product	Accept or recycle
9. General problems typical for many facilities.	Equipment leaks or spills	Accepted in design
	Corrosion	Minimize by design
	Criticality	Gross mass controls; some equipment design
	Plutonium solids form at low acid (<0.1M)	Monitor acidity

Table 3.3-7. Summary of Information on Dedicated Processing Facilities

	Millions of Dollars Capital Cost	Operating Manpower	Development Time (months)	Cold-Test Time* (weeks)	Time for 10 kg Pu (weeks)	Time for 100 kg Pu (weeks)
Spent Fuel (cooled)**	12-24	100	12-24	4-8	1-3	25-35
PuO_2	1/2-1	20	6-9	1-3	1/2-1	9-12
PuO_2 - UO_2 (cold) MOX	1-2	20	8-12	2-4	1/2-1	10-20
Fresh-Fuel (cold MOX) Assemblies	1-2	30	8-12	2-4	1/2-1	10-20
PuO_2 - UO_2 (hot) MOX***	5-10	50	10-15	3-6	1/2-1	15-30****
Fresh-Fuel (hot MOX) Assemblies***	6-12	80	10-15	3-6	1/2-1	15-30****

*Time assumes training of operating personnel using cold materials during construction phase.

**"Cooled" means radioactive at levels one year after discharge.

***Hot means partially decontaminated (or pre-irradiated, in the case of fresh fuel assemblies).

****Time is that allowed for remote maintenance not required for cold facilities.

longer (perhaps by a factor of two or three) if the level of technology and the experience of the staff were minimal.

Individual estimates differ for spent fuel, for spiked fuel materials, and for unspiked fuel materials. However, whether all the differences provide a meaningful discrimination between fuel cycles is unclear. For example, the cost estimates vary up to a factor of ten or more, but all costs are sufficiently low to be within the resource limits of nations with nuclear-power plants. Small operating staffs are needed for such facilities. The processing time to recover materials for a few weapons is a matter of weeks in any case.

The clearest difference is between spent fuel and plutonium once it has been separated and converted to oxide. Thereafter, the incremental differences are less substantial, and their significance is less clear especially when considered in the light of the uncertainties to which these estimates are subject.

4. SAFEGUARDS FOR ALTERNATIVE FUEL CYCLES

4.1 INTRODUCTION

4.1.1 Nonproliferation and Safeguards

The preceding assessments have concentrated on identifying and comparing the proliferation-resistance features of alternative fuel-cycle systems. The assessments have been performed in the context of existing safeguards, protective measures and other institutional provisions that may apply and have identified opportunities for improving proliferation resistance.

The nature and status of IAEA safeguards, and some possibilities for future improvements, are discussed in this chapter. National safeguards are also discussed here because: IAEA safeguards are based on the verification of information supplied by national safeguards systems; technical features intended to increase the proliferation resistance of fuel cycles may affect national physical protection systems designed to protect against subnational threats; and nuclear material stolen by a subnational group in one country could subsequently be used by a nation for proliferation.

4.1.2 IAEA Safeguards

The IAEA was founded in 1957 to "accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world. It shall ensure, as far as it is able, that assistance provided by it or at its request or under its supervision and control is not used in such a way as to further any military purpose."

The IAEA is authorized to apply safeguards to special fissionable and other materials, equipment, facilities, and services to ensure that they are not used to promote any military purpose. Such safeguards are not intended

to prevent diversion, to identify or apprehend a diverter or to recover diverted material. These are the responsibilities of individual governments. Similarly, IAEA safeguards are neither intended nor designed to search for undeclared or clandestine facilities.

The Board of Governors of the IAEA has approved two major documents which define in some detail the nature of safeguards agreements between a nation and the IAEA. The first of these, INFCIRC/66/Rev. 2, 1968, describes the Agency's safeguards system for nuclear materials or facilities submitted unilaterally by a nation or under a bilateral or multilateral agreement. It may apply to some or to all of the nuclear materials and facilities within a nation. The second, INFCIRC/153, 1971, describes the content and structure of an agreement between the IAEA and nations as required by the NPT. A NNWS party to the NPT agrees to accept safeguards on all source and SNM in all peaceful nuclear activities within its territory or under its jurisdiction or control. In addition, Britain, France, and the U.S. have volunteered to place their peaceful nuclear activities under safeguards. Both documents oblige the IAEA to make a determination of compliance with the terms of the safeguards agreement and to report noncompliance to the Board of Governors.

Any nation which has become party to the NPT or volunteered its civilian nuclear-power facilities for IAEA safeguards presumably has concluded that to do so will enhance its national security. For this reason, it will want the IAEA safeguards applied to be effective and credible. Accordingly, each nation under safeguards should feel obliged to cooperate fully with the IAEA inspections of its facilities. In this way, each nation can utilize IAEA safeguards as a means of providing credible assurance to other nations that no diversion is taking place.

IAEA and National Safeguards Systems

Under INFCIRC/66/Rev. 2, a nation pledges that those materials or facilities submitted for safeguards will be used only for peaceful purposes. These materials and facilities may not include all sensitive materials and facilities in a nation. NNWS's which sign and ratify the NPT undertake to accept safeguards on all nuclear materials in <u>all</u> of their peaceful nuclear activities and to abstain from nuclear-weapons proliferation. In both cases, the agreement between the IAEA and the nation requires that the purpose, size and type of operation of each relevant facility be described.

A nation which is party to the NPT is required to establish a system of accountability and control for nuclear materials subject to IAEA safeguards. This national safeguards system generally supplies the IAEA with inventory and flow information about nuclear materials which the IAEA must verify.

Agreements pursuant to INFCIRC/66/Rev. 2 do not specify just how IAEA inspectors are to verify measurements and reports supplied by the national system. The NPT and INFCRC/153, however, specify that the IAEA is to perform its verification activities at "strategic points" which are to be defined in each IAEA-facility agreement, or Facility Attachment. Facilities of a nation are divided into material balance areas (MBA's). An MBA is a physically defined space containing process material and equipment. In the agreement between the nation and the IAEA, the key measurement points (KMP's) are defined for the MBA's. There are two types of KMP's, flow measurement points and inventory measurement points. The flow KMP's are used by IAEA to verify the flow of material between MBA's, and the inventory KMP's are used to verify the materials within the MBA during a physical inventory.

IAEA Objectives and Responsibilities

The objective of IAEA safeguards agreements is summarized in paragraph 28 of INFCIRC/153, which states, "the Agreement should provide that the objective of safeguards is the timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection."

In order to fulfill its responsibility, to be able to detect diversion of "significant quantities of nuclear material" in a "timely" manner, the IAEA has defined significant quantity in relation to the amount of nuclear material needed for a nuclear explosive, and timeliness of detection in relation to the time that it might take a nation to convert the nuclear material into a form suitable for use in a nuclear weapon. For the purpose of designing its safeguards procedures at nuclear reactors and processing facilities, the IAEA has tentatively adopted quantitative goals (goal quantities) as opposed to safeguards requirements, for significant quantities and detection times for the different types of nuclear material which may be subject to safeguards. These are presented in the following Tables 4.1-1 and 4.1-2.

Table 4.1-1. Quantities of Safeguards Significance

Material	Quantity of Safeguards Significance (SQ)	SQ Applies to:
	"Direct-Use" Material	
Pu	8 kg	Total Element
^{233}U	8 kg	Total Isotope
$U(^{235}U \geq 20\%)$	25 kg	^{235}U
Plus rules for mixtures where appropriate.		
	"Indirect-Use" Material	
$U(^{235}U < 20\%)$ *	75 kg	^{235}U
Th	20 metric tons	Total Element
Plus rules for mixtures where appropriate.		

*Including natural and depleted uranium.

Table 4.1-2. Estimated Material Conversion Times

Material Classification	Beginning Material Form	End Process Form	Estimated Conversion Time
1.	HEU*, U-233 Metal or Pu	Finished Uranium or Plutonium Metal Components	Order of days (7-10)
2.	HEU, U-233 oxide or other pure compounds. PuO_2, $Pu(NO_3)_4$ or other pure compounds.	"	Order of weeks ** (1-3)
	MOX or other non-irradiated pure mixtures of U [(U-233 + U-235) $\geq$ 20%] or Pu. HEU, U-233, or Pu in scrap or other miscellaneous impure compounds.	"	"
3.	HEU, U-233, or Pu in irradiated fuels ($\geq 10^5$ Ci/Kg HEU or U-233 or Pu)	"	Order of months (1-3)
4.	Uranium containing < 20% U-235 and U-233; thorium	"	Order of one year

*Uranium enriched to $\geq$ 20% in the isotope U-235

**While no single factor is completely responsible for the indicated range of one to three weeks for conversion of these uranium and plutonium compounds, the pure compounds will tend to be at the lower end of the range and the mixtures and scrap at the higher end.

IAEA Safeguards Activities

The principal IAEA safeguards activities are the negotiation of safeguards agreements, examination of the facility design information attached to the agreements, review of the accounting reports and various other reports provided by the nation, and the collection of information by inspection for verification of design information, ad hoc and routine inspections, and special inspections.

The activities of the IAEA in the course of ad hoc, routine, and special inspections are for collecting information whereby the IAEA can independently establish that the information provided by the nation is:

- Complete in its coverage of all nuclear material that has been present in the MBA
- Accurate in terms of the conformity of the nation's measurement data (random and systematic errors) with internationally accepted standards of measurement accuracy
- Formally correct, that is, free of mistakes
- Valid with respect to the actual location, identity, quantity, and composition of all nuclear material subject to safeguards.

Once an agreement is in place, the IAEA activity is verification of the material balance data of the nation and its facilities. This verification is based primarily on material accountancy, "the safeguards measure of fundamental importance, with containment and surveillance as important complementary measures." INFCIRC/66 or 153 requires measurements, maintenance of records of nuclear materials on hand and in process, and monthly reporting to the IAEA. IAEA's material accountancy function is based on the independent verification of the quality and accuracy of the individual facility records and reports.

The IAEA procedure is to make randomly selected independent measurements of materials in process and in inventory, and to compare these measurements with the operator's reported measurements, in order to determine whether or not the reported values are reliable and to assess any deliberate or unintentional

bias. On the basis of its verification activities, the IAEA determines the MUF and the LEMUF to compare with those given by the operator.

The purposes of containment and surveillance are to help achieve timely detection of diversion, to help ensure that nuclear material transfers in the area of observation are recorded and reported to the IAEA, and to facilitate inventory verification. Containment features built into a facility, to the extent that these are verifiable, are accepted by the IAEA. Surveillance measures are applied by the IAEA. They may depend on the activities of inspectors or may involve technical aids, such as closed-circuit TV. An important technique is the use of seals to indicate that a container, vault, or LWR has not been opened since the seal was attached.

Importance of IAEA Safeguards

The importance of IAEA safeguards lies in the degree of assurance which they can provide the community of nations that nuclear materials and facilities are being used for peaceful purposes. This assurance depends upon perceptions of the effectiveness of IAEA safeguards in realizing their purposes.

An assessment of the effectiveness of IAEA safeguards must take account of the specific responsibility assigned to the IAEA, the manner in which IAEA safeguards reinforce or complement other international measures, and the practical limitations of the present and possible future procedures which the IAEA can or might apply. A reasonable assessment of the IAEA should focus on what the IAEA can do and avoid any expectation that it provide assurances which are technically or politically impossible.

The IAEA's combination of material accountancy, and containment and surveillance activities make the probability of detection significant. Nevertheless, it is the would-be proliferator who is left to assess the deterrent effect of safeguards in weighing the advantages that he perceives of attempting to make one or a few nuclear devices against the chances and consequences of being detected by the IAEA. The chances of being detected are discussed in Volume II. The consequences of being detected by the IAEA depend on how other nations would react to its report, while the IAEA itself can require the return of the materials and equipment made available under its auspices.

To prevent or at least discourage a would-be national proliferator from undertaking the attempt, IAEA safeguards should appear sufficiently credible either to deter covert diversion or to require overt withdrawal from safeguards agreements. Thus it is that all nations have a strong interest in providing assurance to one another that they are meeting their nonproliferation commitments and all parties have an interest in supporting the IAEA and in improving its operations.

4.2 SAFEGUARDS FOR CIVILIAN NUCLEAR-POWER SYSTEMS

4.2.1 Once-Through Fuel-Cycle Systems

Reference Once-Through System with a Light-Water Reactor

The major safeguards concerns about the reference once-through system with an LWR are the enrichment plant and spent-fuel handling and storage. Safeguards for the once-through systems except spent-fuel are discussed here; safeguards for spent fuel are discussed in section 4.3.3.

The terms of the IAEA NPT safeguards agreements become applicable when uranium is in a pure form suitable for enrichment or for fabrication of reactor fuel. For LWR's, IAEA safeguards start at the plant which converts "yellowcake" from the mill into UF_6, as feed for enrichment; they continue to be applied to the uranium throughout the rest of the fuel cycle.

Enrichment -- All enrichment technologies, present or projected, have some potential for the production of weapons-grade uranium. Their proliferation resistance is highly dependent on whether they are compatible with effective and acceptable safeguards that can provide for timely detection of the production of HEU in a commercial fuel plant. Enrichment plant safeguards should provide the means for IAEA to verify independently that LEU is not being diverted and that no HEU is being produced. Specifically, the IAEA should be able to detect the production of a significant quantity of HEU in a short enough time (at least within a few weeks) to permit an effective international requirements for IAEA access, determine the necessary frequency of inspection,

develop criteria for material accounting, and define at least the broad requirements for containment and surveillance devices and systems. But IAEA safeguards have not yet been applied to any enrichment plant.

Nevertheless, enrichment plants are the only nuclear facilities where the generation of an off-design HEU product is a primary concern. IAEA efforts have attempted to define the level of access and prerequisites needed before an effective level of safeguards can be contemplated. However, more intensive forms of IAEA safeguards may prove necessary to ensure against covert plant modification for HEU production. This internal IAEA presence would have to be carefully balanced against the risk of inadvertent disclosure of sensitive information.

This possibility requires considering the sequence of steps that a nation must undertake to perform a covert enrichment:

- Separation of a kind consistent with HEU production must be provided. This may require no more than control adjustments to the existing plant or batch recycling, but for some future systems, major equipment modifications of the process may be required.
- Uranium feed must be provided either by undeclared entry from outside or by removal from declared stocks in the plant.
- HEU enrichment operations must be conducted.
- The product must be removed from the facility.

If any single step can be effectively detected in time for effective action, then the safeguards objective is theoretically fulfilled. Good systems practice will require some degree of safeguards redundancy to improve confidence in a detection and to reduce false alarms. While it is fundamental that inspectors and monitors be able to detect any diversion, a safeguards system must also be politically acceptable and cost-effective.

Table 4.2-1 summarizes the current status of the requirements for detection of diversion in each stage of the commercial technologies examined in Chapter 3. The entries indicate whether perimeter or internal observations

Table 4.2-1. Inspector Access Conditions Required to Safeguard Effectively against All Steps of a Diversion

	Gaseous Diffusion	Centrifuge	Aerodynamic	AVLIS	MLIS	PSO	Chemical Exchange
Provide separation capacity							
Minor preparation	I(o)	I(o)	I(o)	NA	NA	NA	
Major preparation	P(c,o)*	I(c,o)	P(c,o)*	I(o)*	I(o)*	I(o)*	
Provide feed							
Introduce undeclared feed	I(c,o)	I(c,o)*	I(c,o)	I(c,o)	I(c,o)	I(c,o)	
Acquire declared feed	I(o)	I(o)*	I(o)	I(o)	I(o)	I(o)	
Perform enrichment	P(o)*	I(o)	P(o)*	I(o)	I(o)	I(o)	
Remove product	I(o)	I(o)	I(o)	I(o)	I(o)	I(o)	

Code I - Interior access necessary

P - Perimeter access to walls surrounding sensitive components necessary

NA - Not applicable

(c) Indicates during construction phase

(o) Indicates during operational phase

* - Indicates minimally intrusive opportunity for effective detection

(or measurements) are required for detection and whether safeguards are required during both construction and operation to detect the introduction of undeclared feed or equipment. The minimally intrusive opportunities for effective detection are indicated to emphasize the belief that an internal IAEA presence may be required in some cases.

The existing situation with regard to enrichment safeguard capabilities can be summarized as follows:

- Material accountancy is the safeguards measure of fundamental importance. Measurements of UF_6 flows at enrichment plants are very accurate compared to the measurements of uranium at other parts of the nuclear fuel cycle. At the largest uranium enrichment plants, the sensitivity of material accountancy might not, of itself, enable the detection of the diversion of a goal quantity of either 75 kg of U-235 contained in LEU or 25 kg of U-235 contained in HEU. Nevertheless, material accountancy will play a key role in safeguards at any enrichment plant.

- For completeness and continuity of knowledge, containment and surveillance measures will be required. The IAEA will need to verify that the enrichment plant is being operated as declared and that all uranium feed, product, tails, and waste discards flow through agreed-upon KMP's. In the interest of efficiency, the measures of accountancy, containment, and surveillance will need to be coordinated and adapted to the characteristics of the particular facility and the terms of the particular agreement between the IAEA and the nation.

- Existing safeguards techniques are estimated to be effective only with access to the cascade areas. To be effective, other levels of access require intensive inspection efforts to provide a high level of assurance that material is not diverted. R&D on new safeguards techniques requiring less intensive efforts while providing the same level of assurance should be undertaken.

- It is anticipated that a nation may wish to request a special MBA which would place restrictions on the access of IAEA inspectors to some of the process areas. In such a case, the IAEA and the nation must consider compensatory measures since it is incumbent upon the Agency and the nation to agree on safeguards measures by which the IAEA can fulfill its responsibility.

Conversion and Fabrication -- LEU fuel-fabrication plants receive UF_6 from an enrichment plant. The UF_6 cylinders are heated to convert the fluoride from a solid to a liquid; ammonia is added; the precipitate is heated and reduced to UO_2, a dry powder. After this chemical conversion process, the UO_2 powder is formed into ceramic pellets; the pellets are encapsulated in long, thin rods; and the rods are mounted in assemblies, containing from about 50 to 200 rods. The annual reload for a 1,000 MWe power reactor contains about 30 tons of uranium. Typical fuel-fabrication plants are designed to provide fuel for from 10 to 50 reactors, that is, to process from 300 to 1500 tons of uranium in the form of UO_2 per year.

Since LEU is not considered to be an attractive target for subnational groups, LEU fuel-fabrication plants are not designed with special containment features. For this reason, and because the timeliness goal is not demanding, IAEA safeguards at these plants are based almost entirely on material accountancy. The most important accountancy measure is to ensure that all UF_6 cylinders received at the plant are measured and that these measurements are verified. The more time-consuming activity is verification of the annual or semiannual physical inventory, since this will be many tons, possibly a few hundred tons, of material in a variety of forms, such as pure powder, unsintered and sintered pellets, rods, assemblies, reject materials awaiting recovery, and dirty scrap and waste in a variety of inhomogeneous forms.

With state-of-the-art measurement accuracy and statistical analysis, an LEU fuel-fabrication plant operator may achieve an LEMUF of 0.25%. With its verification procedures, the IAEA might be able to detect a loss of 0.5%, which means that diversion of a goal quantity, 75 kg of contained U-235, may be feasible in plants with annual inventories of 500 metric tons throughput.

Reactors -- The features of a reactor which are of interest from the point of view of IAEA safeguards are: (1) the composition of the fresh fuel, and the size and shape of fuel assemblies (or the nature of the fuel if it is not in the form of assemblies), (2) the fresh-fuel management system, (3) the reactor fuel loading-unloading process (periodic, on-line, etc.), (4) the spent-fuel management system, and (5) structural features which may facilitate safeguards (e.g., containment) or interfere with safeguards procedures (e.g., limitations on access for verification of inventory).

LWR's are sealed while in operation. Fuel can be transferred only after the reactor has been shut down and allowed to cool for several days. The fuel consists of large, discrete assemblies containing from 50 to 200 thin fuel rods up to 12 meters long. Accountancy is based on identifying and keeping track of the fuel assemblies.

The fuel rods in an assembly may have several different enrichments, ranging from 1 to 4%, and the mean enrichment may vary from one assembly to another. On the average, the enrichment of the uranium in LWR fresh fuel is about 3%, and a full core contains about 100 metric tons of uranium. Since the IAEA goal quantity is 75 kg LEU of contained U-235, the goal quantity is about 2-1/2% of a full core load. In most cases, the IAEA would have applied safeguards at the fuel-fabrication plant, and applied seals prior to shipment. At the reactor, the seals would be checked. When the reactor is shut down for reloading, IAEA inspectors should be present to observe and to record which irradiated assemblies are removed and which fresh assemblies replace them, and to verify that there are no unrecorded fuel assemblies. Between reloadings, seals may be attached to the lid of the reactor vessel.

The major inspection effort is directed toward the verification of the inventory of spent fuel at the reactor. Surveillance instruments (cameras) are used to monitor the storage pool. Inspectors check the pool and read the surveillance record a few times per year. While it is easy to count the assemblies in a pool, it is difficult to read the identifying symbols, and it is impossible to verify visually that some rods are not dummy substitutes. Operations at some reactors include taking assemblies apart to replace leaking rods, a practice which may make verification more complicated.

Since there are, and will be, many more reactors than bulk processing facilities, it is important that techniques be developed to minimize inspector effort at reactors. Considerable progress is being made: seals which can be read acoustically in the pool have been developed to ensure that rods have not been changed and to facilitate verification of identity; and a variety of surveillance devices which have tamper-indicating features and which could be queried, for example, by telephone, in lieu of an inspector visit are under development.

Improved Light-Water Reactors and Other Once-Through Systems

Alternative modifications to LWR's include the higher burnup of LEU in the reactor and the use of uranium/thorium fuels in the reactor. Most of the proposals for improving the resource utilization of LWR's would have but minor impact on the safeguards procedures or effort. Extended burnup would involve fewer fuel elements but not affect procedures and would have little impact on inspector effort. Dismantling assemblies in the pool to retrieve rods with low burnup would probably call for inspector surveillance during the operation.

Fuel containing uranium enriched to about 20% and thorium has been suggested as a way to reduce uranium requirements. The LEU in this fresh fuel has somewhat higher strategic value than 3 to 5% enriched uranium or natural uranium. The spent fuel would contain one-third to one-tenth as much plutonium as do the present LWR and HWR spent fuels. Nevertheless, the spent fuel would require accountancy and surveillance. Some increased safeguards effort might be required in accounting for the fresh fuel because gamma-ray NDA techniques to measure enrichment of UO_2 fuels perform poorly, if at all, when employed on uranium and thorium mixtures. Active neutron interrogation techniques can be employed, but are much less convenient for use by IAEA inspectors.

Heavy-Water Reactors -- The once-through HWR fuel cycle is similar to the LWR except that enrichment is not required and that heavy water must be produced as the moderator. The conversion process following the uranium mine and mill produces UO_2 powder which goes directly to fuel fabrication.

The conversion process is not necessarily located at the fabrication site, in this case. IAEA NPT safeguards would begin at the product end of the process which converts natural U_3O_8 to UO_2. The fuel-fabrication operations are similar to those employed to produce LEU pellets, rods, and assemblies. The annual uranium requirements for a 1,000 MWe CANDU reactor are about 130 metric tons of uranium compared to about 30 metric tons of LEU for an LWR of comparable size, but since the LEU enrichment is about four times that of natural uranium, the accountancy sensitivity is very nearly the same for both types of facility. A major difference is the size and number of fuel assemblies produced per reactor-year. As a comparison, reactors of approximately

1,000 MWe capacity of PWR, BWR, and CANDU design discharge roughly 70, 200, and 5,000 assemblies per year, respectively.

While this fuel cycle eliminates the need for enrichment and thereby eliminates the safeguards problems associated with enrichment plants, it does require plants to produce heavy water by concentrating naturally occurring deuterium by a factor of many thousand.

Heavy water is not a nuclear-weapons material. It can be used, however, as the moderator for a clandestine reactor fueled with natural uranium to breed plutonium. Pure graphite can also be used for this purpose. The Nuclear Suppliers Group has agreed to control the sale of heavy water and heavy-water production plants and technology. In some cases, the IAEA has been requested to apply safeguards to the heavy-water inventory at an HWR that is under safeguards. The plutonium produced in the spent fuel of HWR's is of more concern than the presence of heavy water, and the proliferation significance of enrichment plants is greater than that of plants that produce deuterium from ordinary water.

The natural uranium fuel used in HWR's or the low-enriched fuel which might be used in the future, contains considerably less U-235 than is the case for LWR's. On the other hand, the fuel assemblies, or bundles, are small, there are many more discrete items, and several bundles are loaded into and removed from the reactor each day. It would be easier to push through some assemblies with low burnup to produce weapons-grade plutonium than to do so at an LWR. Canada and the IAEA have an ongoing program for developing of surveillance equipment to verify the transfer operations.

That a CANDU reactor produces more plutonium per MWe than an LWR is not of major safeguards significance. Both produce many goal quantities each year. However, the very large number of small fuel elements discharged requires safeguards procedures which are different from those applied to LWR spent fuel. When assemblies are discharged to the storage pool, they are collected in baskets which, in turn, are stacked in racks. The storage pools are typically designed to store spent fuel for the lifetime of the reactor. Acoustically readable seals have been developed for the baskets. Problems which remain to be solved are ensuring the integrity of the baskets and developing containment and surveillance technology to seal off racks as they fill-up and to verify integrity of these larger units. Also, remote

verification by on-line fueling surveillance equipment would reduce the burden on inspectors.

The resource utilization of HWR's can be improved by replacing the natural uranium in the fuel with slightly enriched (1.2%) uranium. Fuel at the reactor is exposed to substantially higher burnup and the number of assemblies to be monitored is thereby reduced by a factor of two or three. However, the impact of this modification on safeguards at a reactor would not be significant.

HTGR's -- The IAEA has no experience in safeguarding HTGR's reactors. Designs which use LEU only or uranium/thorium cycles in which the uranium is enriched up to 20% would appear to involve similar safeguards considerations as for the comparable fuel cycles in LWR's. On the other hand, current demonstration versions employ HEU as the fissile and thorium as the fertile material. Assemblies for one reactor design are large graphite blocks which are replaced once every 4 years or so (periodic shutdown to replace about one-sixth of the core). Another design has on-line refueling and uses small graphite spheres. Both types of fresh fuel are quite difficult to measure by NDA techniques. Accounting for the fresh fuel is more difficult than it is for LEU or uranium and plutonium fuels. The IAEA would have to rely more than usual on containment and surveillance measures to ensure that materials accurately measured at early processing stages were not diverted or substituted for. On-line fueling would appear to require considerably more safeguards R&D than does the HWR for a comparable degree of assurance.

4.2.2 Closed Fuel-Cycle Systems

The major safeguards concerns about closed fuel-cycle systems are the reprocessing facilities, the presence of weapons-usable material, and spent-fuel handling and storage. Safeguards for the closed systems except spent fuel are discussed here; safeguards for spent fuel are discussed in section 4.3.3.

Reference Recycle System with a Light-Water Reactor

Reprocessing -- The IAEA has limited experience applying safeguards to reprocessing plants. It has conducted safeguards exercises at several reprocessing plants in Belgium, Italy, and the U.S., all of which use the PUREX process, the only reprocessing process presently operated on a commercial scale.

Reprocessing plants are a safeguards concern because they produce material--purified plutonium--which can be used for nuclear weapons with only a little additional work and in a short period of time. Even small plants with a throughput of 300 metric tons of spent fuel per year separate 2 or 3 metric tons of purified plutonium per year.

The IAEA has tentatively chosen quantitative design objectives for implementation of safeguards. At a reprocessing plant, the more difficult goals to achieve are the detection of abrupt diversion of 8 kg of plutonium in one to three weeks, and of protracted diversion of 8 kg of plutonium during one year. Since it is very costly to shut down and to clean out the processing equipment to perform a physical inventory, plant operators would be reluctant to perform such inventories frequently. In these circumstances, the timeliness goal for detection of a diversion cannot be achieved on the basis of six-month material balances by means of material accounting alone. In addition, it may be impossible to achieve the goal of detecting diversion of 8 kg of plutonium over a period of one year because of practical limits for the accuracy of nuclear material measurements. At the present time, a material balance based on measurements made by a careful facility operator might be accurate to within .5% of the throughput. Based on its verification activities, IAEA material balances could be no more accurate. The accuracy of both IAEA and operator material balances can be expected to improve in time, but probably not by more than a factor of two.

It would be difficult by means of material accounting alone to detect diversion of 8 kg of plutonium in a year from a reprocessing plant with an annual production rate of 1600 kg of plutonium, which corresponds approximately to a plant designed to process about 150 metric tons of spent fuel per year. The large commercial plants planned for the future are designed to process 1,500 metric tons of spent fuel per year.

In view of these circumstances, the IAEA has established an International Working Group on Safeguards for Reprocessing Plants to consider procedures and techniques which could enable the IAEA to meet its international responsibilities for the smaller reprocessing plants coming under its purview now, and at the larger facilities now in the planning stage. Several papers submitted in INFCE suggest how credible safeguards may be developed for the larger future plants. These suggestions are briefly summarized below, although many of the details remain to be determined and demonstrated.

IAEA safeguards on spent-fuel commence when the fuel is discharged from a reactor. Accountancy is based on item identification and enumeration. Containment and surveillance measures may be employed in order to confirm the integrity of shipments and to minimize the need to verify the many items contained in storage pools. The IAEA accepts the operator's estimate of the uranium and plutonium content of spent fuel until more accurate values can be obtained after dissolution of the fuel at a reprocessing plant. It is especially important that the IAEA verify the plutonium content at the input to a reprocessing plant since this figure becomes the reference for material accountancy at all the later process stages.

Safeguards at the receiving and storage area of a reprocessing plant are based on item accountancy, supplemented by containment and surveillance measures, as is the case at reactors or other storage facilities. A combination of containment and surveillance instruments and procedural controls should be employed to ensure that dissolver solution cannot bypass the input accountability vessel. The IAEA will need to verify the calibration of the vessel and to ensure that samples taken for verification are truly representative. One possible independent technique to confirm the plutonium content for a batch of spent fuel (about 30 metric tons for an LWR) would employ data on the uranium content of the same fuel elements before irradiation in the reactor, approximate information on the burnup of the batch of fuel in the reactor (based on reactor records or certain indirect methods now being evaluated), and analytical measurements of the ratio of uranium to plutonium in the several dissolver batches.

Most of the chemical separation process takes place behind massive shielding under remote control. There are many pipes and control lines which penetrate the radiological shielding. One possibility is to place containment and surveillance monitoring instruments at every penetration of the barrier. A second possibility is to employ sensors installed for process control and additional sensors to provide a nearly continuous indication of the material

contained in each process vessel. In any case, IAEA inspectors would verify the measurements at the input accountability vessel, the uranium and plutonium product loadout stations, and of the plutonium contained in the several radioactive waste-disposal streams. The IAEA International Working Group is trying to decide how these techniques can best be combined and tested to achieve a high probability of detecting a significant diversion in a timely fashion without placing too great a burden on the IAEA or on the operation of the facility.

The $Pu(NO_3)_4$ product is transferred to criticality-safe tanks for temporary storage and for blending small batches into larger batches with uniform isotopic composition. Such storage tanks should be designed so that they can be calibrated and the contents verified. Containment and surveillance measures should be applied to detect abrupt diversions and to ensure validity of the measurement of withdrawals.

The trend is to locate the plant for converting $Pu(NO_3)_4$ to PuO_2 (or to MOX) adjacent to the reprocessing plant. The safeguards procedures appropriate for such a conversion plant are similar to those appropriate for the process MBA of a MOX fuel-fabrication plant, discussed below.

The PuO_2 or MOX powder would be stored in discrete containers in a shielded and physically protected vault or storage building. Accountancy would be on the basis of discrete, identified items. The containment would ensure that containers pass through the KMP's. Additional containment and surveillance might be applied at a perimeter which should be well defined; and it should be possible to verify the inventory (item identification and seal integrity) on a timely basis. The development of an international plutonium storage regime is also being considered under the sponsorship of the IAEA.

Results of recent safeguards research point to possible improvements in the IAEA's ability to safeguard reprocessing facilities. Improvements of the ability to measure quickly and accurately the concentration of plutonium in dissolver solution using absorption edge spectrophotometry or X-ray fluorescence should allow an inspector to rapidly verify an operator's measurement. Techniques that can provide an accurate measurement of in-process inventory without a shutdown for a cleanout inventory may allow more frequent inventories to be made and thereby improve the timeliness of IAEA's safeguards assessment. And the improvements in containment and

surveillance equipment (acoustically read seals, monitoring of penetrations into the process area, etc.) may allow the IAEA to rely more on containment and surveillance equipment and to use inspectors in other roles.

Some of the fuel cycles considered in NASAP would use reprocessing technologies other than PUREX; for example, any denatured fuel cycle using thorium would probably utilize one of the variants of the THOREX process. The safeguards for the non-PUREX reprocessing variants would be no better than the safeguards for the PUREX process. In fact, with today's measurement technology, the material balances would be more uncertain.

Refabrication -- About one quarter of the makeup fuel of an LWR would be MOX. The rest of the fuel rods containing LEU pellets would probably be fabricated at an LEU fuel-fabrication facility. For this reason, MOX fuel-fabrication plants probably will be about one-fourth the size of their sister LEU fuel-fabrication plants. A large MOX fuel-fabrication plant would process about 300 metric tons of heavy uranium and plutonium metal per year, containing about 12,000 kg of plutonium, which dictates the safeguards implementation design.

Measurement accuracies for MOX fuel are similar to those for LEU fuels. If an LEMUF of 0.25% can be achieved by both the IAEA and the operator, the IAEA might be able to detect that 10 kg of plutonium was missing for an inventory period of two months, a capability close to the design criterion of 8 kg. On the other hand, the timeliness goal for plutonium is one to three weeks, not two months.

The IAEA has recently organized an international working group to assist it in defining safeguards requirements for MOX fuel-fabrication plants, and to identify needs for R&D, test, and evaluation. In the U.S., real-time accounting techniques have been developed and to some degree demonstrated. Using these techniques would require well-defined and credible containment features, provision for installation of process-line sensors and surveillance instruments at critical locations, and the design of key measurement instruments to help inspectors with verification.

LWR Recycle Reactor -- The use of MOX fuel, rather than LEU, will affect the safeguards procedures to be applied to the fresh fuel before it is placed in the reactor. The spent fuel will contain somewhat larger amounts of plutonium which will have had higher burnup than is the case for the once-through cycle, but this higher burnup should not significantly affect the safeguards procedures or techniques for the spent fuel.

It is expected that an IAEA inspector would check the seals on fresh-fuel shipping containers, when they arrive, record the identify of individual assemblies, and their location in the local store. Nations should supply special containment for plutonium-bearing fuels. In that case it might be possible to apply seals to the containment. If the seals or lock could be interrogated remotely, it might not be necessary for an inspector to visit the reactor site every two weeks. The IAEA would like to verify the enrichment of LEU fuel or the plutonium content of MOX fuel after the arrival at the reactor by using NDA techniques. Instruments under development give promise of fulfilling this purpose.

Technical Measures -- Technical modifications which would affect safeguards at reactors are those which would make the fresh fuel dangerously radioactive: spiking, partial decontamination, and pre-irradiation. Each of these would require that the fresh fuel be shipped in heavily shielded casks, perhaps the same as those used for removal of spent fuel. The casks would be opened under water in a part of the spent fuel storage pool and transferred into the reactor by reversing the unloading process. The inspector would check the seal on the shipping cask. Individual assemblies would need to be identified remotely and monitored in much the same fashion as for spent fuel. It would be virtually impossible for IAEA inspectors to verify the plutonium content of the fresh fuel by NDA techniques.

Pre-irradiation calls for design and operation of a special reactor to be installed at the MOX fuel-fabrication plant. Conceptual designs are still so vague that it is not possible to define appropriate safeguards procedures. While but one of these reactors would be required to pre-irradiate the fuel for between 10 and 50 power reactors, all of the fuel would have to pass through the irradiator. For this purpose, the irradiator would be designed either for on-line fueling or for very frequent shutdown to transfer fuel. Measurements at the product end of the MOX fuel-fabrication plant should be accurate and could be automated. From that time on, until after irradiation in a power reactor, storage at the reactor, and ultimate dissolution at a reprocessing plant, accountancy would have to be based on item accounting,

complemented by containment and surveillance. This would appear to require essentially continuous on-site inspection at the pre-irradiation reactor.

The technical modifications which would affect safeguards at the reprocessing plant and the MOX or fuel-fabrication plant include those discussed previously as well as coprocessing. So far as measurements and accountancy are concerned, it does not make much difference whether the fuel-fabrication plant received PuU_2 and UO_2 to be blended on-site, or the plant received a blend of, say, 10% PuO_2 to 90% UO_2, and pure UO_2 to be blended on-site to a consumer's requirements. The degradation in the accuracy of materials accounting would be small and of little consequence for coprocessed material in a high-throughput plant. This degradation may be more than compensated for by the higher risk to the diverter by forcing him to divert much larger quantities of material to obtain a goal quantity of plutonium.

On the other hand, if the feed material should be spiked to a relatively high level with radioactive Co-60 or other fission products, the fuel-fabrication line would need to be designed with additional shielding and for remote, rather than manual, maintenance. The radioactivity would also affect the measurement program of the IAEA and the operator. To avoid the greater cost and time required to draw and to analyze samples would require sacrificing the accuracy of the measurements. The more massive and less penetrable shielding around the process lines should enhance the value of the containment; the higher radioactive levels should improve the sensitivity of surveillance equipment; but, the added radioactivity probably would seriously degrade the performance of NDA instruments, both those used outside the process equipment by inspectors and those which might be installed on-line for real-time accounting purposes. In such cases, the design of IAEA safeguards would need to be reconsidered, and substantial development and testing would be needed to determine the impact on costs, level of effort, and overall system performance.

Alternate Recycle Systems

Light-water reactors operating on denatured uranium/thorium fuels, and the concomitant U-233 recycle, have been considered. The more important safeguards, as well as proliferation-resistance considerations, on this fuel cycle pertain to the supporting facilities required to supply make-up U-233 or U-235, and the reprocessing plant. Safeguards for an LWR using these

fuels would be rather similar to the procedures employed now with LEU fresh fuel, though the goals for fuel containing U-233 are more stringent than those for fuel containing U-235. In any case, the quantitative design goals would be less stringent than for MOX fuels.

Accounting for the fresh fuel would include verification of the contents of fresh rods and assemblies at the fuel-fabrication plant, seals on shipping containers, identification and accounting for fresh fuel assemblies upon arrival at the reactor and during storage at the reactor, and observation of the fuel-reloading process. Beyond this step, the safeguards procedures would appear to be the same as for reference recycle.

As was mentioned previously, the IAEA would like to be able to confirm the enrichment, fissile-to-fertile ratio, by NDA at a reactor. Both passive and active NDA techniques are being developed for this purpose. Passive gamma-ray techniques probably can be employed to measure the U-235/fertile ratio, but the U-233 fertile ratio would be very difficult to measure by passive gamma-ray techniques (because of interference by U-232 daughter radiations). If an active interrogation technique can be developed which would be feasible for use by IAEA inspectors, it should work as well for either type of fuel.

Since the timeliness goal is less stringent than for plutonium fuels, neither weekly inspections nor sophisticated surveillance equipment appear to be necessary. Since it would take many years to establish this fuel cycle, future developments in safeguards technology may further reduce the safeguards effort needed.

HWR's have been operated with MOX fuel. The higher plutonium content of the fresh fuel and spent fuel in such operation of HWR's places higher stress on the safeguards system for those reactors. The safeguards problems associated with on-line refueling and spent-fuel storage are made more acute by operating with MOX.

In LWBR's, the fresh fuel would contain large amounts of U-233, for which the IAEA quantity and timeliness design goals are the same as those for plutonium. It would be necessary to design credible accountancy, containment, and surveillance equipment and procedures for the fresh fuel. As for other

U-233/thorium fuels, passive gamma-ray assay of fresh fuel would be very difficult. Active neutron interrogation techniques should be applicable technically if they can be made operationally feasible. Because of the intense, high-energy gamma-ray emissions associated with U-233 fuels, the shielding and remote-handling equipment which would be incorporated might provide a substantial degree of containment for the fresh fuel.

Fast-Breeder Systems: A Summary Account

The LMFBR uses two types of fresh fuel, a MOX fuel in the core, and natural or depleted UO_2 in the blanket. The plutonium concentration in the core pellets is in the range of 16%, four to five times the plutonium concentration in the MOX fuel pellets that would be used in LWR's. Both core and blanket fuel for published LMFBR designs would be in the form of physically large, identifiable assemblies, each containing a large number of long, thin fuel rods. An important difference between an LMFBR and an LWR is the nature of the coolant, liquid sodium in the first case and ordinary water in the other. Refueling would be periodic, about once a year, in both cases. Present designs anticipate that fresh-fuel assemblies would also be stored in a vessel filled with liquid sodium. Upon removal from an LMFBR reactor vessel, the spent-fuel elements would be transferred by remote control to the same vessel. This general design is characterized by a high degree of containment and by near zero visibility.

The LMFBR fuel cycle as a whole requires that the plutonium be extracted from the spent fuel and fabricated into fresh MOX fuel for the core. There would, of course, be excess plutonium. The fuel cycle involves the reprocessing and recycling of much more plutonium than would be the case for recycle in LWR's. The external flows and supporting facilities present safeguards problems which are similar to those involved in the recycle system, but perhaps more difficult to resolve satisfactorily because of the larger quantities of plutonium flowing into or out of the reactor.

A variety of possible fuels have been considered for use in fast-breeders.

At present there are a few small pilot-plant fuel-fabrication plants which can process one to a few metric tons of plutonium per year into MOX fuel

for the core, and a similar amount of natural or depleted UO_2 fuel for the axial and radial blankets. If breeders become commercial in the next century, future production facilities probably would range in capacity from 10 to 50 metric tons per year of plutonium.

As in the recycle system, fuel fabrication may start with the coprecipitation of UO_2 and PuO_2 or with the blending of the two dry powders. Pelletizing operations are similar. The pellets are sealed into rods and the rods firmly mounted in assemblies.

At the larger fuel-fabrication plants it would not be possible to meet the quantity and timeliness goals assumed here by using present-day technology. It is expected, however, that measurements for accounting would be more accurate for improved production control as well as for safeguards by the time that such facilities are in operation. It is also expected that the process lines and storage vaults would be highly instrumented and that containment and surveillance should be a well-established methodology.

If acceptable IAEA safeguards can be designed and demonstrated at the enrichment, reprocessing, and plutonium facilities now being built, it would encourage the belief that it should also be possible to design and apply acceptable safeguards for the large fast-breeder fuel-cycle facilities.

At the reactor, the plutonium containing fresh-fuel assemblies for the core would be of primary concern for diversion. While the spent-fuel assemblies from core and blanket would contain even more plutonium, the fact that they are radioactive and require remote reprocessing to recover the plutonium makes the spent fuel like that of once-through or recycle fuel cycles (spent fuel from the blanket might represent a somewhat more attractive target for diversion because of the low Pu-240 content of the contained Pu). The IAEA would verify the uranium and plutonium content of fresh fuel rods and assemblies at the fuel-fabrication plant and seal the shipping containers. At the reactor, the seals would be removed, the individual assemblies identified, and their transfer to local storage observed as far as possible. The last point at which they could be observed may be at the complicated, remote-controlled equipment which would transfer the assemblies into the liquid sodium storage vessel. IAEA inspectors might be able to observe

reactor operators during the annual refueling operation, when spent fuel is removed from the reactor and transferred to the storage vessel and fresh-fuel assemblies travel a reverse path, all by remote control. Removal of any fuel elements from the storage vessel would require operation of the machinery used to extract spent fuel for shipment to the reprocessing plant.

Each core fuel assembly may contain more than a goal quantity of plutonium. The provisional timeliness goal is one to two weeks. Because of the extensive containment which would exist and the limited means to withdraw fuel from the storage vessel, special emphasis could be assigned to developing tamper-revealing surveillance equipment and means for remote monitoring. It would also be desirable that the remote-controlled equipment provided for fuel transfers be designed in such a way that the IAEA could verify the identity of the assemblies being transferred.

Some of the other fast-breeder reactor designs would be rather similar to the LMFBR as far as safeguards are concerned. The timeliness goals for denatured fuels are longer, but accounting and surveillance procedures would not otherwise be greatly affected. Breeders of the LMFBR design but employing plutonium in the core and thorium in the blanket to produce U-233 for denatured LWR fuel would present safeguards problems similar to those discussed for the LMFBR which breeds plutonium. Fresh core assemblies would contain large amounts of plutonium. Blanket assemblies (and pellets in axial rods) would contain U-233 chemically separable from the thorium. The quantity and timeliness goals would not change. The verification difficulties associated with an LMFBR design would be the same.

A GCFR, with helium as the coolant, and fuel rods and assemblies rather similar to those for a sodium-cooled reactor, would provide less in the way of built-in containment, but it would be relatively easy to verify the identity of fresh-fuel or spent-fuel assemblies.

4.3 SAFEGUARDS FOR ASSOCIATED SENSITIVE FACILITIES AND ACTIVITIES

4.3.1 Research Reactors and Critical Facilities

The nuclear materials and operations associated with research reactors and critical facilities have several characteristics that affect the safeguards applied to these facilities. Some of these characteristics are:

- The nuclear material is generally contained in discrete items.
- The composition of the nuclear materials may be LEU, HEU, U-233, or plutonium.
- The facility may be shutdown frequently for changes of experiments or other reasons.

The form of the fuels is amenable to item counting during physical inventories. The IAEA could use surveillance devices to monitor the status of the fuel between physical inventories. The records of the surveillance devices should be analyzed frequently in order to achieve the timeliness of detection goals.

4.3.2 Transportation of Sensitive Materials

All fuel cycles involve the transportation of nuclear materials and fuel assemblies and storage of such fuel at reactors awaiting refueling. The ability of the IAEA to meet its timeliness goals must be considered. Presumably the IAEA would rely on the use of item accountability and seals for containment and surveillance to provide the desired timeliness goal for LEU, but the timeliness goals for materials containing HEU, PuO_2, and MOX are more difficult to achieve since the transportation involved may take longer than a week or two.

If the time during which any sensitive material is in transit exceeds the timeliness goal, special measures are required to detect diversions with the appropriate timeliness.

Three concepts for safeguarding nuclear material in transit vary, not with respect to the distance traveled, but with respect to the time-interval goal for verification and the safeguards measures that may be suitable.

First, the concept of periodic shipping-receiving comparison is based on the comparison and correlation of material transfer records at the origin and destination of shipments, and on the accountancy records maintained at a monitoring agency. For this concept, the timeliness-of-detection goal by the IAEA should be no less than the transit time. For nuclear material with short timeliness goals, these procedures may be inadequate, and additional methods may be needed.

Second, the concept of IAEA escorts assumes continuous IAEA escort of the transportation vehicle from the point of origin to the destination and has a capability for rapid detection of diversion of the shipment during transit.

Third, the concept of remote surveillance is based on a monitoring system which uses a remote communication link to verify the presence and integrity of the material in its container during transit between origin and destination. If this system proves to be successful, it could provide nearly instantaneous detection of anomalies, depending only on the time interval chosen for communication. As such, it has some potential for allowing the IAEA safeguards system to meet appropriate goals for timeliness.

In addition to the detection of anomalies, one must consider the additional time which would be required for the IAEA to investigate the anomaly and to establish whether the circumstances were indicative of a diversion or not. In cases where the transport link is land-based, this investigation would require the IAEA to determine the location of the transport vehicle, travel to the site, and study the circumstances. In the case of sea transport, the investigation of circumstances surrounding the report of an anomaly would clearly be more complex and difficult for the IAEA to perform.

4.3.3 Spent-Fuel and Waste Repositories

Safeguards may be applied to certain classes of wastes produced in once-through or closed fuel-cycle systems. Wastes bearing enriched uranium and plutonium from various fuel cycle facilities would be considered in the IAEA verification of material balances for these facilities. The requirement for ongoing safeguards on these waste materials at a waste repository may not be required.

IAEA documents INFCIRC/66/Rev. 2 and INFCIRC/153, state that safeguards may be terminated "upon determination by the Agency that the material is consumed, diluted in such a way that it is no longer usable for any nuclear activity relevant from the point of view of safeguards, or has become practicably irrecoverable." With the exception of spent fuel, recycle UO_2, and, possibly, depleted uranium tails from enrichment activities, fuel-cycle wastes are likely to meet the IAEA criteria for termination of safeguards.

Concepts for the application of IAEA safeguards to spent fuel at a repository are discussed below. The procedures for safeguarding recycle UO_2 and depleted uranium tails should be similar in principle, though differing in detail. Other waste would probably be less concentrated and so less attractive for national diversion, and thereby require less stringent safeguards.

Spent Fuel

The spent fuel from any fuel cycle is highly radioactive and also contains some Pu or U-233, which can be extracted chemically. While extraction of Pu or U-233 from radioactive spent fuel requires that the fuel be transported in large, heavily shielded containers, and that all operations and transfers be performed by remote control and behind massive shielding, the appropriate techniques are matters of public knowledge; the operations to be performed do not call for the highest degree of sophistication. While the diversion of spent fuel is not easy, and the clandestine construction of a dedicated chemical-separation plant probably presents substantial difficulties for many nations, the substantial amounts of spent fuel at every reactor and the existence of many reactors in many different nations suggest that the

safeguarding of spent fuel may place the biggest burden on IAEA resources unless techniques can be developed to lighten it.

AFR storage may soon be required for LWR and possibly other reactor spent fuel. From the point of view of proliferation resistance, it would be desirable that a few large AFR storage facilities be established on a regional, multinational, or international basis to serve the needs of several nations. These facilities should be designed to facilitate safeguards. Features of concern to the IAEA are the design of the receiving and removal areas to facilitate identification of fuel assemblies and to permit the use of NDA instrumentation to confirm identities, and the design of the storage pool so that assembly seals can be queried or credible surveillance equipment can be installed and used.

Dry-storage as well as wet-storage depositions are being considered for LWR and HWR fuels. It does not appear to be possible to read the identity symbols on assemblies in dry storage. It is possible that remotely readable seals attached to individual assemblies or groups of assemblies in wet storage might be developed. Alternatively, external containment and surveillance measures might be emphasized. In any case, special attention must be paid to identifying assemblies received or shipped and to keeping track of their proper location in between.

Once-through fuel cycles include the possibility that spent fuel might eventually be shipped to a waste repository for permanent disposal. Safeguards for spent fuel at such a repository should continue until such time as the IAEA might determine that the spent fuel is no longer recoverable. It is generally considered that spent fuel of whatever form would be encapsulated in substantial containers before burial in a repository. In the case of LWR spent fuel, for example, the procedures of item accounting, NDA confirmation, containment, and surveillance would be continued into the encapsulation plant. If the IAEA is to continue accounting for material item-by-item after encapsulation, it would be necessary to observe the encapsulation process and to attach appropriate seals to the new outer containers. There would be advantages to the IAEA in locating the AFR storage pool and the encapsulation process at the geologic repository location. With these operations located separately, there would need to be buffer storage for spent fuel at the encapsulation plant and the repository. Colocation would eliminate these buffer stores or at least substantially reduce their size. Because of the one-way flow of radioactive wastes into a geologic repository, it is possible that item-identity accounting could be replaced by simply item counting supported by containment and surveillance measures when the canisters are

sent to the lift and transferred to the deep underground burial level. If the encapsulation were to take place at the minehead, containment and surveillance might provide adequate assurance that the spent fuel received could go nowhere but down. If so, it would be sufficient to count the containers after encapsulation, to count the containers lowered to the repository, and to count the containers placed in each burial room. On a sampling basis, inspectors might check some of the operations. To ensure that no canisters were removed, radiation detectors could be installed at various places to provide assurance that all flows were one-directional. If the facility were designed for retrieving the spent fuel at a later time, the safeguards design would need to be more complicated than has been suggested.

As the fuel canisters are emplaced and the rooms backfilled, the possibility for direct measurement is eliminated, while containment is enhanced and the opportunities for recovery (diversion) become limited. The repository may remain accessible for some period of time to verify that the chosen method of disposal is indeed safe. During such a period, containment and surveillance will need to be continued at an appropriate level. After a repository has been backfilled, closed, and deactivated, later recovery of the spent fuel would require a substantial effort of multiple drilling, remining, or, in the case of disposal in salt, solution mining. Any such effort probably would be time-consuming, expensive, and difficult to conceal. Should the IAEA consider it desirable to continue its surveillance, it would probably be sufficient to send an inspector to the site two to four times a year.

4.4 NATIONAL SAFEGUARDS

The objectives of national safeguards systems are different from those of the IAEA. National systems should deter subnational adversaries, prevent theft or diversion of HEU or plutonium for construction of a nuclear weapon, theft of radioactive materials for dispersal, and sabotage of nuclear facilities or shipments by a small group of dissidents or terrorists. Such systems must also be prepared to respond effectively to adversaries who are not deterred. The objective of IAEA safeguards, on the other hand, is "the timely detection of diversion..." and "...deterrence of such diversion by the risk of early detection."

The effectiveness of national safeguards systems is of international interest for at least two reasons: (1) Nuclear material stolen in one country can be

used to threaten people in another country; and (2) IAEA accountancy is based on verification of national accounting for nuclear materials.

A nation should be able to ensure that no potential subnational group could have access to enrichment or reprocessing equipment, or to a reactor for converting uranium or plutonium, whereas the IAEA assumes that a national adversary might have access to such facilities. Consequently, a nation may have only minimal requirements for the physical protection of natural or low-enriched uranium but stringent requirements for the protection of plutonium and high-enriched uranium. A nation may require extensive physical protection for power reactors to prevent sabotage, whereas preventing sabotage of reactors is not the responsibility of the IAEA. IAEA requirements on accounting for natural or low-enriched uranium, and for spent fuel, may be more strict than these might be for internal national security reasons.

A national safeguards system is often described as consisting of two complementary sets of procedures: material control and accounting, and physical protection. The system as a whole should restrict access to nuclear materials and sensitive areas, and place multiple barriers in the path of any potential subnational group, including personnel granted access to the materials. A nation can control access, employ armed guards, and pursue criminals. The IAEA, on the other hand, is limited to observing, auditing, and verifying measurements.

A nation has the basic responsibility to design and enforce national safeguards on behalf of national security and in fulfillment of its agreements with the IAEA. A nation may delegate some responsibilities to the administration and operators of nuclear facilities, subject to its regulations and inspection. In the U.S., the NRC licenses nuclear facilities, issues safeguards requirements, and performs inspections of privately-owned and possibly a few Government owned nuclear facilities. DOE applies "equivalent" safeguards to the Government-owned nuclear facilities. These agencies require that all nuclear material be accounted for and that strict physical security measures be applied to quantities greater than 5 kg of U-235 contained in uranium enriched to more than 20% or 2 kg of U-233 or plutonium at any facility or in any single shipment.

As an example of a national safeguards system, the NRC system is defined in Part 10 of the Code of Federal Regulations (10 CFR) and further explained in

NRC Division 5 Guides. Although material control and accounting regulations appear in one section of 10 CFR, these are, in fact, two sets of procedures. Material accounting requires that all receipts, shipments, and significant internal transfers of nuclear materials be measured, that accurate and up-to-date accounts be maintained, that physical inventories of all materials on hand be performed at specified intervals, and that the book-physical inventory difference (generally referred to as Material Unaccounted For or MUF) be determined, as well as the limit of error of the difference (or LEMUF). A quality assurance program for the measurements performed and for an assessment of the LEMUF is required.

Material control, on the other hand, establishes administrative and procedural measures to deter or to detect diversion by authorized personnel promptly, and to reduce opportunities for falsification of records. The management of a nuclear facility is required to establish a material control and accounting (MC&A) organization, parallel to and independent of the organization responsible for handling and processing the nuclear materials. Each production facility is required to define MBA's and item control (storage) areas, each with its containment. Both shipments and receipts are to be carefully measured. Shipper-receiver differences are to be reported and resolved. Internal transfers between material balance and item-control areas are to be measured and witnessed by an operator and an MC&A representative. Both organizations participate in a physical inventory and review the computation of MUF and LEMUF. The MC&A and physical security regimes interact to deter or to thwart internal adversaries.

A separate line organization is also required for administration and operation of the physical protection system. As for the MC&A organization, written procedures, personnel requirements, and performance assessment plans are to be approved by NRC. Multiple physical barriers are required for reactors and other facilities with more than trigger quantities of HEU or plutonium. A facility is located in a protected area to which access and egress of material and personnel is controlled. Nuclear materials are contained within material access areas, in storage vaults or within process equipment. Other areas may be designed for special protection if they contain equipment vital to health, safety, or safeguards operations. Personnel are authorized for admission to the protected area and to such internal control areas relevant to their activities. Physical protection operations are directed from a secure command center. Communications are provided within the facility and with the local police department. Individuals are searched for weapons and explosives when entering, and for nuclear material when leaving material access areas. Incoming and outgoing packages require authorization and are subject to inspection by guards, MC&A, and other personnel. The physical protection

system is intended to prevent access by stealth or deceit (false identity), to protect against forceful entry by armed outsiders and, together with MC&A, to counter internal threats.

The responsibility for prompt detection and response to internal threats is placed on the material control and physical protection systems. Material accounting may also play a role but its primary functions are to maintain current records on the status and location of nuclear materials, to support the application of IAEA safeguards, and to provide assurance that all material is accounted for after a physical inventory has been performed. When a material balance indicates a significant difference between the expected book value and that measured by the inventory, a search is instituted to explain and correct the difference. Frequently, determining the cause of the discrepancy reveals ways to improve the MC&A procedures.

Technical measures are under development to provide greater protection of materials entering, within, or leaving item-control areas, and to perform partial or complete inventories at frequent intervals. It is expensive and time-consuming to shut down and clean out process equipment for a physical inventory. Near-real-time accounting systems have been developed and demonstrated for some processes involving HEU or plutonium. To some extent, these systems make use of the information on material flows and inventories in equipment needed for quality process operation and control. To these are added weighing devices, radiation, and other sensors so that a running material balance can be performed for each unit process, process stage, or vessel. The large amount of data from the many sensors is fed directly to a computer and subjected to sophisticted statistical analysis to detect either sudden anomalies or longer term trends which should be examined.

A major concern for a national safeguards system is protection of power reactors against sabotage. From a national point-of-view, material control and accounting at a reactor is relatively simple. Fresh and spent fuel in the form of assemblies is uniquely identified by serial number. Once fuel is placed in the reactor storage vault or pool, it is well protected by the containment of the building and the physical protection required to prevent sabotage. As with other sensitive nuclear facilities, the NRC requires that the reactor be surrounded by a protected area with barriers, special lighting, intrusion alarms, and guards. Access to the protected area, to the reactor, and to vital areas, is tightly controlled. Measures are also taken to prevent sabotage attempts by employees or others permitted access.

Since there are many more reactors than supporting production facilities, and since the intensity of effort required to protect one type of reactor is much the same as that for another, the choice of fuel cycle probably will not have a major impact on the size or costs of a national safeguards program.

4.4.1 Once-Through Fuel-Cycle Systems

For a national safeguards system, personnel at mines, mills, and the facilities which convert yellow-cake to UO_2 or UF_6 would be required to make measurements, to maintain records, and to submit reports. Since natural uranium is not very radioactive and subnational adversaries presumably could not make much use of such materials, there would be no special requirements for physical protection.

The LWR fuel cycle requires that natural uranium be enriched to 3 to 5% U-235. National inspectors would have free access to all parts of an enrichment plant and could ensure that the equipment was being used as declared. The measurements of UF_6 are typically in the range of 0.1% (more accurate than for other nuclear materials). Outside of the cascades, the UF_6 is contained in large, very heavy metal cylinders with identifying numbers. These offer little attractiveness for subnational groups and could only be stolen with large fork lifts and big trucks. The amounts of uranium in waste streams is a very small fraction of the throughput.

Since facilities for fabricating LWR (or CANDU) fuel are also unattractive targets for subnational groups, only limited physical protection measures are likely to be required to assist the IAEA and to deter or to detect diversion. Weighing, sampling, and chemical analytical measurements are capable of achieving a comparatively high degree of accuracy, adequate for detection of diversion of the substantial amounts which might have national significance. Both the utility that purchases the fuel and the nation which oversees its activities will be interested in the content and quality of the finished fuel.

Spent fuel is stored at the reactor at least for several months and probably for several years. In the once-through fuel cycle, spent fuel may be shipped to an AFR storage facility for interim storage and ultimately to a

waste-disposal facility for permanent emplacement in a geologic repository. A nation probably will require some physical protection of the spent fuel in transit and in storage to discourage sabotage attempts. It should also require the maintenance of good records on the nature and location of all radioactive wastes, before and after burial, and for as long a time as is deemed necessary.

4.4.2 Closed Fuel-Cycle Systems

Recycle in Light-Water Reactors

In addition to the national safeguards for the reference once-through fuel cycle, additional safeguards for reprocessing, refabrication, and shipments of MOX fuels for recycle fuel cycles are also necessary. However, safeguards for spent fuel during and after burial would not be necessary since, spent fuel would be stored at the reactor for months or years and then shipped to a reprocessing plant.

Each nation will consider the advantages of recycling plutonium and the costs in terms of proliferation and domestic safeguards risks. The domestic safeguards risks, in addition to the risk discussed above that reactors might be sabotaged, include the possibility that plutonium might be diverted or seized by subnational groups to fabricate a crude nuclear explosive, to disperse plutonium in a highly populated area, or to sabotage new processing facilities and plutonium-containing shipments. However, the additional facilities and shipments add very little to the targets for sabotage, which the power reactors already represent, and are perhaps somewhat easier to protect. In short, the costs of safeguarding plutonium and the risks of failure, compared to the economic and other advantages which plutonium recycle offers, have to be considered by any nation contemplating the use of such fuel cycles.

Since the possible consequences of a crude nuclear explosive appear to be very serious, a nation would design a safeguards system employing the material control, accounting, and physical protection items described earlier, in order to reduce such risks to an acceptable level. While such measures would not eliminate the possibility of diversion of gram amounts of plutonium for dispersal,

they would reduce the possibility of such threats significantly. They would also reduce the possibility that the additional facilities might be sabotaged.

Any nation which permits the processing of HEU or plutonium will become susceptible to hoaxes, that is, to threats by subnational groups that they have obtained such materials and intend to exploit them. (Such threats could also be made to other governments.) To assess such threats and to be sure that they are not real, the national safeguards system should be able to verify whenever necessary, the location of all sensitive materials.

Fast-Breeder Systems

This fuel cycle involves the same facilities and materials as the reference recycle system. In time, however, breeder reactors might reduce or eliminate the need for enrichment plants. The major differences between recycle and fast-breeder systems are that FBR's employ a higher concentration of plutonium in the fresh fuel for the core, and that the quantities of plutonium reprocessed and recycled per reactor are several times greater. While it may be premature in the absence of experience to assess the impact of breeders on national safeguards, the following observations can be made.

FBR's, like LWR's may be vulnerable to sabotage. Both types of reactors should be designed to reduce such vulnerability as far as possible. However, it is likely that substantial physical protection will always be required.

Safeguards risks do not necessarily increase proportionately with the amounts of sensitive nuclear materials, the number of facilities, or the number of shipments. Accounting for small amounts of material is easier than for larger amounts because fewer measurements are required and measurement errors would not conceal a diversion. Above some threshold, each facility or shipment may become a potential target for armed robbery or covert diversion. A subnational group would need only one target quantity of material at a time. Any nuclear facility having 10 kg of plutonium might be a target. But if the 10 kg were not all in one place, it might take many hours to extract it. A nuclear facility with one ton of plutonium would appear to be a more likely target, and one with 10 tons rather similar. The industrial security effort applied to the larger of these could make the larger facility less vulnerable

to theft or diversion than the smaller one since there would appear to be a sort of economy of scale for safeguards at nuclear facilities.

Any significant plutonium recycle in a nation would involve a large number of shipments of plutonium bearing fuels each year. The FBR fuel cycle would involve substantially more shipments per reactor, each containing many kilograms of plutonium. Since a subnational group would probably be interested in seizing only one shipment, it would appear that the quality and reliability of the physical protection provided for shipments of nuclear materials is more important for assessing national safeguards risks than are the frequency of such shipments.

Technical Measures

Certain technical modifications to fuel-cycle operations have been suggested as possible ways to improve the proliferation resistance of closed fuel cycles. Some of these have been studied by the U.S. in the past, particularly with regard to the application of national safeguards. The conclusions of these previous studies are briefly summarized here:

Colocation -- In 1975, Congress required the NRC to study the safeguards and other advantages of colocating various types of nuclear facilities. NRC concluded that the colocation of reprocessing and refabrication plants would have the advantage of eliminating shipments of PuO_2, and that the costs of safeguards probably would be reduced because of the concentration of plants and of the physical protection forces. It would have little effect on the costs for material control and accounting. However, the NRC concluded that, from a national perspective, it would not be excessively expensive or difficult to provide highly effective physical protection for the shipments of PuO_2 from reprocessing to separately located MOX fuel-fabrication plants, and that economic considerations, rather than safeguards, might be the determining factor for the location of these facilities.

Coprocessing -- An NRC study of this subject in 1975/6 arrived at inconclusive results. Coprocessing was not considered to make a significant difference for diversion within the reprocessing plant iteself since diversion by plant personnel would be difficult whether the plutonium and oxide blend

were a direct product of, or were formed by blending separate liquid streams before loadout of, the nitrate solution product. What was of more concern was the vulnerability to theft or diversion of the PuO_2 or the MOX after conversion. It is conceivable that clever subnational groups might fabricate an inefficient but destructive nuclear explosive using PuO_2 rather than plutonium metal. Shipments from reprocessing to refabrication plants and materials at both plants would have an additional barrier should the product be MOX. Different nations may draw different conclusions as to the costs and benefits of coprocessing.

Spiking -- It has often been suggested that the spiking of plutonium-bearing fuels by the addition of highly radioactive materials (e.g., Co-60) or by the deliberate retention of some of the radioactive fission products at reprocessing might provide a radiation barrier which would discourage or deter subnational groups. A study of this subject conducted by the NRC in 1975 reached the following conclusions. For detection purposes spiking can increase the effectiveness of containment and surveillance measures but at the expense of impaired accuracy in material accountancy using present techniques. For deterrence purposes spiking levels up to tens of thousands of rem/hr could be expected to deter subnational groups to an extent similar to spent fuel. This, however, is a choice to be made by individual nations in selecting their safeguards systems. It must be emphasized that current and proposed IAEA safeguards procedures would require complete redesign. Most NDA measurement techniques would be severely compromised, and even classical chemical analytical methods would be hampered. It was also recognized that the NRC would have to support the argument that this costly procedure, with its added risks of accidentally exposing the public to radiation, involved less risk to the public than improved safeguards measures.

Post-irradiation -- Post-irradiation refers to the irradiation of fabricated MOX fuel before shipment from a refabrication plant to a reactor. It would not affect the need for high-level safeguards measures at a refabrication plant, a reprocessing plant, or for the shipments between them. It would make any fresh fuel seized during transport or from the storage vault of a reactor highly radioactive. The comments on spiking on safeguards for sensitive shipments, and on physical protection at reactors are relevant.

Use-Denial Techniques -- NASAP supported a study of active and passive techniques which might be employed at national or multinational facilities to ensure that if the host nation were to seize a facility, such as a reprocessing plant, it could not use it immediately for the production of

nuclear-weapons materials. The advantages and disadvantages of the use of such techniques to control proliferation are discussed elsewhere. They have also been considered for use in national safeguards programs and deserve further study. "Use denial" is not the same as physical barriers which would impede a would-be proliferator or an armed attack, although they are related, as techniques. For example, a plutonium storage vault might be rigged to be filled with plastic foam in the event the facility were attacked. This technique could substantially delay the subnational group in achieving its goal and provide time for a large number of police to respond to the alarm. An example of a use-denial technique which a nation might consider in an emergency would be a mechanism to blend natural or depleted uranium with HEU so that the subnational group could not make a nuclear explosive if it could succeed in its attempted seizure of nuclear material. All of these techniques can only supplement those barriers already put in place under more conventional national safeguards programs and practices described above.

4.4.3 Transportation

From a national point of view, the materials of most concern for safeguards are HEU and plutonium and shipments of radioactive materials which might be dispersed locally while in transit or seized for dispersal elsewhere. Materials that might be seized in transit for dispersal elsewhere are shipments of plutonium, spent fuel, highly radioactive nuclear wastes, and a few nonnuclear radioactive shipments (Co-60, Cs-137, etc.). The hazards associated with the sabotage of nuclear or radioactive shipments are often comparable to the hazards associated with the sabotage of shipments of other hazardous materials in common use.

National safeguards would emphasize physical protection. In the U.S., physical protection involves the use of specially designed vehicles, preplanned routes, schedules, and communications. Sensitive DOE nuclear materials are shipped in "safe-secure-vehicles," a tractor and a trailer of special design. The cab of the tractor provides some protection for the driver and his partner. The trailers are designed to withstand highly sophisticated penetration techniques for a substantial time. The tractor-trailer is accompanied at a distance by one or more small vehicles carrying armed guards. All vehicles in the convoy are equipped with radio communications among themselves and to a central U.S. office. Any suspicious incident can be reported to the headquarters in minutes and notice sent to local police either directly or from the central dispatcher.

5. GLOSSARY

Assay	Analysis of material to determine the concentration of fissile material
Back end	That part of a fuel cycle beginning with the reactor and including reprocessing, recycling of fuel, waste treatment, and disposal
Batch recycle	A procedure whereby a product is reintroduced as feed in subsequent cycles. Here used to achieve either greater enrichment or additional chemical separation
Breeder (reactor)	A reactor that produces more fissile material than it consumes
Cascades	Conventionally connected stages of parallel-connected units separating different isotopes of uranium
CIVEX	Conceptual process for extracting uranium and plutonium from spent fuel for use in reactors so that plutonium is never separated from uranium or all the radioactive fission products (see reference 14 of Section 2.2 in the Bibliography)
Centrifuge	Enrichment technique whereby different atomic weights of uranium isotopes permit their separation by "spinning;" in the case of uranium, by spinning uranium hexafluoride gas.

Cladding	Material that surrounds and separates the reactor fuel from the coolant
Closed	Mode of fuel-cycle operation whereby spent fuel is reprocessed for re-use as fuel
Co-conversion	Reprocessing technique whereby the mixed-oxide fuel is produced from a mixture of uranium and plutonium nitrates so that the PuO_2 never exists in separated form
Cold	Material of very low radioactivity
Colocation	The juxtaposition of sensitive facilities in a single location to minimize the number of sites requiring safeguards and the number of transportation links
Converter	Reactor that produces new fuel while it also produces energy
Cool	Material that is not highly radioactive
Coprecal	Proprietary process for preparing MOX
Coprocessing	Reprocessing technique whereby the product is a mixture of uranium and plutonium, not plutonium alone
Critical facility	Low-power experimental reactors operating at low neutron flux levels, with little fuel burnup and little induced radioactivity; used to confirm design calculations

Chemical barrier	The difficulty in separating mixed chemicals
Dedicated facility	A plant, usually for enrichment or reprocessing, used to produce or fabricate weapons-usable materials
Denaturing	A process of isotopically diluting a fissile material so that the mixture is not directly weapons-usable
Diffusion	Enrichment technique
Diversion	The removal of safeguarded materials from the fuel cycle
Enrichment	Process of increasing the concentration of one isotope relative to another, usually U-235 relative to U-238
Equilibrium time	The time required to achieve a balance in enrichment or breeder processes, between input and output
EURODIF	French-led consortium (including Italy, Spain, Belgium and Iran) supplying enrichment services using French gaseous-diffusion technology
Fabrication	The process whereby fuel materials are converted into fuel assemblies for use in reactors
Fast-breeder	A type of reactor that produces more fissile material than it consumes

Fertile	A fertile material is one capable of being transformed, directly or indirectly, into a fissile material by neutron capture. There are two naturally occurring fertile nuclides, U-238 and Th-232. When these nuclides capture neutrons they are converted into fissile Pu-239 and U-233, respectively.
Fissile	That which undergoes fission by low-energy neutrons
Fission	The process whereby the nucleus of an atom breaks into two more parts
Feedstocks	Materials used as feed for a given process
Front end	That part of a fuel cycle beginning with the raw materials and ending with fresh fuel elements
Fuel assemblies	Elements of fuel materials suitable for use in reactors
Fuel burnup	Measure of the energy produced by nuclear fuel
Heavy water	Water with hydrogen in the isotopic form known as deuterium (D), or D_2O
High-enriched uranium (HEU)	Uranium in concentrations greater than 20%; enrichments of 90% and more are often used in making weapons-related estimates
Hot	Highly radioactive material

Independent path	A means to nuclear weapons that does not involve civilian nuclear power
In-system	That which is a part of the nuclear-power fuel cycle under consideration
Isotopic barrier	The difficulty in separating mixed isotopes
Isotope	A form of an element determined by the number of neutrons in its nucleus; isotopes react in chemically similar ways
Isotope separation	The process of separating isotopes; usually separating isotopes of uranium (U-233 and U-235 from U-238) as a step toward enrichment
Light water	Water (H_2O); distinguished from heavy water
Low-enriched uranium (LEU)	Uranium in concentrations to less than 20%; enrichments of 3 to 5% are common in light-water reactors and are not used in nuclear weapons
Mixed oxides (MOX)	Mixture of uranium and plutonium oxides (UO_2 and PuO_2)
Natural uranium	Uranium that has not been enriched; natural uranium consists of 99.3% U-238, 0.7 U-235, and traces of U-234 (U-233 does not occur naturally.)
Nondestructive assay (NDA)	Assessment of fissile concentration of fuel without affecting it physically

Off-design	Mode of operation for which the facility was not designed but which can be achieved by its modification
Once-through	Use of fuel in a nuclear reactor without subsequent reprocessing end reuse
On-line fueling	Continuous fueling process whereby fresh fuel is inserted into the reactor while it operates
Open	Mode of fuel-cycle operation whereby spent fuel is placed into interim or permanent storage
Out-of-system	That which is not part of the nuclear-power fuel cycle under consideration
Partial decontamination	Partial removal of fission products from the output of reprocessing plant
Plutonium (Pu)	Element produced from uranium, capable of sustaining fission reactions
Prebreeder	Reactor which prepares fuel for a light-water breeder reactor
Pre-irradiation	Introduction of high levels of radio-activity into fuel assemblies by insertion in a reactor before shipment
Proliferation	The movement toward or the acquisition of nuclear-weapons (or nuclear-explosives) capability by a nation or subnational group presently without it

PIPEX	Conceptual scheme for the physical design and layout of sensitive fuel cycle facilities to reduce access to sensitive material, particularly plutonium, in reprocessing plants (see Reference 4 of Section 2.2 in the Bibliography).
PUREX	Commercial process for separating uranium and plutonium from spent fuel
Pyrometallurgy	Noncommercial process for separating uranium and plutonium from spent fuel
Reactor	A facility for utilizing nuclear energy for various purposes, including power
Recycle	Multiple use of fuel in a fuel cycle
Reprocessing	Process for treating spent fuel to recover unused fuel, usually U-235 and plutonium
REDOX	A particular reprocessing technique
Research Reactor	Any reactor used to investigate nuclear properties or applications
Separative work unit (SWU)	(See note to Table 3.1-1)
Safeguards	The objectives of the international safeguards system are the timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection

Sensitive	That which involves information not available to the public and important to the design, construction, fabrication, operation, or maintenance of a uranium enrichment or nuclear fuel reprocessing facility, or of a facility for the production of heavy water.
Spent fuel	Fuel material which has been removed from a reactor as no longer capable of efficient use
Spiking	Process for adding radioactive contaminants to fissile materials to make them difficult to handle or process
Stage	Conventionally, smallest component in enrichment process for separating different isotopes of uranium
Stretching	Changing operating conditions in enriching uranium to increase the enrichment
Tails	Uranium from enrichment process depleted in isotope U-235
Thermal	Refers to use in reactors which employ slow-moving neutrons
Thorium	Natural element which can be transformed into fissile material through neutron irradiation
THOREX	A chemical process for separating thorium from spent fuel
UCOR	South African process for enrichment

Uranium (U)	An element; see natural uranium
URENCO	Joint British, Dutch, and West German organization operating gaseous centrifuge facilities
Weapons-usable	That which can be used directly in weapons

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