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# IS PLUTONIUM REALLY NECESSARY?

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# IS PLUTONIUM REALLY NECESSARY? *

## I. Introduction, Summary, and Conclusions

### A. Distinguishing Between Safe and Dangerous Activities

There are not separate "peaceful" atoms and "military" atoms. All nuclear activities, whether labeled "peaceful" or not, contribute to the capacity to develop nuclear weapons. But, and this is the central point to understand, not all civilian nuclear activities are equally dangerous in terms of their contribution to nuclear weapon development. In particular, not all aspects of civilian nuclear power are equally dangerous.

As a world, we have probably passed the point where it will be possible for long to deny any country access to nuclear electric power. But, although the ongoing spread of nuclear power plants without doubt increases the potential for further proliferation, not all activities associated with nuclear power contribute equally to proliferation potential. On the one hand, enrichment facilities (especially centrifuge or laser facilities) or spent-fuel reprocessing facilities provide a nation with a ready source of the fissile material necessary to fabricate nuclear explosives. Experts generally agree that obtaining fissile material is by far the hardest part of manufacturing nuclear explosives; thus activities that result in providing a country with explosive-grade material are particularly dangerous from a proliferation standpoint. On the other hand, if spent fuel is not reprocessed, the operation of a light-water reactor (LWR) or natural-uranium heavy water reactor (HWR) does not contribute much to the development of nuclear explosives.

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*Presented at the Cumberland Lodge Conference on the Spread of Nuclear Technology, Windsor Great Park, England, ~~May 26-27,~~ 1976.

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A central question with respect to policies aimed at preventing proliferation is whether any meaningful preventive measures are possible if non-weapon countries are to be permitted to acquire nuclear power reactors. We believe the answer is a qualified "yes," but that the qualification is essential. Meaningful anti-proliferation policies require clear recognition that some civilian nuclear activities are too dangerous to be permitted in non-weapon countries. Possession of civilian nuclear power plants need not *automatically* bring a country unacceptably close to nuclear weapon fabrication, but this is only true so long as certain fuel-cycle alternatives are not implemented. Any fuel cycle that results in a country's having significant quantities of separated or easily-separable plutonium (such as that in mixed uranium and plutonium oxide fuels) makes irrelevant whether or not the country has actually exploded a nuclear device. It could perfectly legally conduct all of the non-nuclear steps in the fabrication process, bringing it to within a few days or weeks of an actual nuclear explosive capability. Although guarantees against the use of the in-country stocks of plutonium might exist on paper, they would mean little in an emergency of the type that would make the country consider fabricating and using nuclear weapons.

## B. Safeguards and Plutonium

As Albert Wohlstetter has pointed out,* acceptance of the principle that some fuel-cycle activities are too dangerous to be permitted non-weapon countries conflicts with one commonly held definition of "safeguards,"

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*Albert Wohlstetter, "Spreading the Bomb Without Quite Breaking the Rules," presented at the conference on the Spread of Nuclear Weapons, Cumberland Lodge, Windsor Great Park, England, May 26-28, 1976.

which interprets the word so as to permit any non-explosive nuclear activity that is subject to international inspections. He has suggested that we need to return to the original notion that safeguards were intended to provide "timely warning" of nuclear weapon development. Application of safeguards defined in this way would effectively prohibit the most dangerous fuel-cycle activities in non-weapon countries. Gaining general agreement on the need to define and apply safeguards in this way will not be an easy task. An important question is whether making the effort is worthwhile, and the answer to this question, in turn, revolves critically around the issue of the necessity for using plutonium as a nuclear fuel.

The issue of plutonium fuel is critical because there is no way to safeguard (in the "timely warning" sense) plutonium in fresh fuel rods. A single reload of mixed-oxide fuel for a 1000 MW light water reactor might contain as much as 1000 kg of plutonium, enough for, perhaps, 50 nuclear weapons. Since the reloads must obviously be physically in a country before they are loaded in a reactor, general use of mixed-oxide fuels would give countries with light water reactors a readily and quickly obtainable source of weapons material. Thus, if plutonium fuels come into common use, the NPT, IAEA inspections, and other anti-proliferation measures will merely constitute a facade behind which countries can legitimately come as close as they desire to a nuclear weapons capability.

The prospects for developing effective non-proliferation policies, therefore, depend upon the feasibility of keeping plutonium out of the nuclear fuel cycle. The purpose of this paper is to assess the feasibility of this objective.

## C. Is Plutonium Fuel Essential?

A commonly held view in the nuclear community is that use of plutonium fuel is essential to nuclear power, that there is no reasonable alternative to plutonium fuel in the long run, and that the sooner we begin using it, the better off we will be. In evaluating this statement, a number of points need to be made.

First, there is no *technical* necessity to use plutonium as nuclear fuel so long as supplies of U-235 are available to use as fuel. In fact, at the present time, none of the commercial reactors in the world use plutonium fuel. And, there is enough U-235 in the world to fuel all present and planned reactors for at least many decades to come. Thus, we should be clear that there is no short-run technical necessity for plutonium use. Plutonium use in the current generation of nuclear reactors is, therefore, a question of economics and not of technical necessity.

Second, statements about the desirability of early plutonium recycle generally refer to light water reactors (LWR's). Heavy water reactors (HWR's) use natural uranium as fuel and provide little economic incentive for using plutonium fuels. Plutonium recycle for HWR's would still be very unprofitable under conditions that might make it profitable (in the narro economic sense) to recycle plutonium for LWR's. Candu reactors, which are favored by many of the countries whose nuclear weapon aspirations are of most concern, are heavy water reactors. However, since most countries planning to have HWR's also will have LWR's, plutonium recycle only in LWR's d not substantially limit proliferation dangers.

Third, the assertion that use of plutonium fuel will be necessary in the long run is essentially an assertion that we must eventually rely on "breeder" reactors to satisfy our electric power needs. Breeder reactors require plutonium (or, another dangerous fuel, U-233) in their fuel cycle; thus, if breeders are essential, so is plutonium. But, in discussing the "necessity" for breeders, we are once again in the realm of economics. Even now, we could (at some very high price) begin to build capacity to produce solar-generated electricity. In the future, the cost of solar power seems certain to decline. Perhaps, also, fusion power will be successfully developed before world supplies of fossil fuels and natural uranium are exhausted to the point where alternative energy sources are required. Thus, breeders will never be essential in the strictly technical sense, but rather <u>may</u> provide an economically attractive alternative source of power. There are, however, very great uncertainties about when, and even if, breeders will become economically superior to other alternatives.

In summary, then, widespread use of plutonium fuels is not a technical necessity but rather a technical alternative that might be economically desirable at some point in time.

## D. The Benefits of Deferring Plutonium Recycle

This paper presents a detailed analysis of the economics of recycling spent fuel products in light-water reactors in the United States. The important conclusions of this analysis are that:

1. It is uncertain at this time whether near-term implementation of recycle would lead to net economic gains or losses, although losses seem more likely.
2. Even if fuel-cycle uncertainties were resolved favorably for the profitability of recycle, the impact of recycle on the cost of nuclear power would be insignificant (a reduction of less than 1 percent in the average delivered cost of nuclear-generated electricity).

As we have just explained, reprocessing and recycle of plutonium will substantially increase the proliferation dangers of civilian nuclear power. It will also add to environmental and terrorist risks. These "costs" of recycle, although difficult to quantify, appear sufficiently large to justify foregoing a large benefit in order to avoid them. But, the potential benefits of recycle in LWRs are uncertain at best, and at the upper limit, not significant in comparison to the overall costs of nuclear power.

These considerations argue strongly for a decision to defer reprocessing of spent fuel to recover fissile products until such time as

1. recycle in LWRs can be shown with high confidence to yield economic benefits sufficiently great to compensate for the large non-monetary (proliferation, terrorist, and environmental) costs; or
2. the viability of the breeder as an important commercial source of power has been demonstrated.

Given the small upper-limit benefits from recycle in LWRs, the second possibility seems far more likely to provide a justification for reprocessing and use of plutonium. But when, and even if, the plutonium breeder will become competitive with thermal reactors is very uncertain. The U.S. does not plan to decide whether to build a commercial prototype for ten years. Problems and delays may push this decision even further into the future. European development programs are further along than the one in the U.S., but important technical problems remain to be solved. Nor, is it by any means certain that these programs will produce a breeder that is competitive with the then-current generation of LWRs. This will require not only finding good solutions to the technical problems, but also that LWR fuel cycle costs be sufficiently high to compensate for the higher purchase cost of the breeder. When this might occur is extremely uncertain. If the time scale of breeder commercialization stretches sufficiently into the future, the possibility arises of developments that could obviate the need for the plutonium breeder. If this were to occur, the initial decision to defer plutonium recycle could result in entirely avoiding the risks inherent in widespread use of plutonium fuels.

Thus, deferring recycle offers the hope that plutonium fuel can be avoided altogether. If recycle becomes obviously desirable, all that will have been lost by deferral will be the benefits lost during the period of deferral, benefits which will be extremely small at best. By contrast, if we decide now to go ahead with plutonium use and it turns out to have been a mistake, the proliferation costs will already have been borne, with little chance of reversal. And, the nuclear industry will have burdened itself (and us all) with political, environmental, and economic problems worse than any it would otherwise face.

Although the issue of plutonium recycle seems to be viewed by nuclear proponents as a crucial battle in the war against the anti-nuclear "nit-wits," analysis shows that the outcome will have little effect on the economics of nuclear power. Engaging in this battle will require the nuclear proponents to use inordinate amounts of political capital and technical talent. Yet, if the battle is won, the major effect seems likely to be a further substantial increase in opposition to nuclear power. Given that public acceptability appears to be the primary obstacle to continued growth of nuclear energy, friends of nuclear power would do well to consider thoughtfully whether continued advocacy of immediate recycle serves well their own objectives.

## II. The Economics of Plutonium Recycle

### A. Relative Cost of Plutonium Fuel

Recycling of plutonium involves:

1. Separation of plutonium (and uranium) from spent fuel by a chemical-mechanical process generally referred to as reprocessing;
2. Fabrication of the plutonium into new fuel rods, generally referred to as mixed-oxide (MOX) fuel fabrication because such fuel contains both uranium and plutonium oxides;
3. Transportation of the fuel rods to the reactor, a relatively costly procedure because of the risk of terrorist diversion;
4. Treatment, transportation, and storage of the radioactive waste products produced at reprocessing and fabrication facilities.

Additional physical security costs will be incurred at various points in the fuel cycle at points other than fuel rod transport in order to guard plutonium from terrorists.

The alternative fuel cycle without reprocessing and recycling involves the following major steps:

1. Mining of uranium;
2. Enrichment of uranium (for LWR's but not HWR's);
3. Fabrication of uranium oxide fuel rods;
4. Transportation and storage of the highly radioactive spent fuel elements.

Whether or not recycling will be profitable involves the relative future prices of all of the steps in the two alternative cycles, prices most of which are highly uncertain and some of which are entirely unknown.

The most important uncertainties are:

- Future prices of uranium
- Future costs of reprocessing
- Relative waste treatment and storage costs under the two alternatives
- The costs of protecting plutonium from terrorists

Because the uncertainties are many and large, no single calculation of comparative costs should be given much weight. But it may be helpful to cite an example to show how various factors enter into the comparison. The example in Table 1 is for prices in 1975 dollars that we consider reasonable (but highly uncertain) for the U.S, in the early 1980s, if reprocessing is given regulatory approval.

Costs of ultimate storage of spent fuel and radioactive wastes, as well as plutonium-recycle, physical security and safeguard costs, have been left unspecified. They are omitted from the analysis because there is not yet any clear definition of how these parts of the fuel cycle are to be carr out, making impossible meaningful estimates of cost. Inclusion of ultimate storage costs would make the case less favorable to mixed-oxide fuel, since as explained in detail in the next section, such storage requirements will be greater with reprocessing and plutonium recycle than without.

For the prices specified in Table 1, recycle fuel is about 70% more expensive than fuel made from virgin uranium. It is to be stressed that this particular result is very sensitive to the prices involved. Several points are worth noting:

## Table 1

## COMPARISON OF URANIUM OXIDE AND MIXED OXIDE FUEL COSTS
(Prices in 1975 Dollars)

### A. Fuel Cycle Cost of 1 Kg of 3.4% U235 Fuel

| Input | Quantity | Unit Price | Total |
|---|---|---|---|
| Uranium | 6.2 kgU | $ 65/kgU | $ 403 |
| Enrichment | 5.2 SWU | 100/SWU | 520 |
| Fabrication | 1 kgU | 100/kgU | 100 |
| Spent Fuel Transport and Disposal | | | ? |
| Total | | | $1,023 + ? |

### B. Fuel Cycle Cost of 1 Kg of Equivalent Mixed Oxide Fuel

| Input | Quantity | Unit Price | Total |
|---|---|---|---|
| Reprocessing to Obtain Pu(1) | 4.9 kgU | $320/kgU | $1,568 |
| Credit for Recovered U(2) | 4.9 kgU | 66/kgU | (323) |
| $U_3O_8$ | .95 kgU | 65/kgU | 62 |
| MOX Fabrication(3) | 1 kgU + 34 gms $Pu_f$ | 100/kgU + $8/ gm $Pu_f$ | 372 |
| Radioactive Waste Transport and Disposal | | ? | ? |
| Physical Security and Safeguard Costs | | ? | ? |
| Total | | | $1,679 + ?? |

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(1) Includes transportation of spent fuel to the reprocessing plant, waste management at plant, and conversion of plutonium nitrate to plutonium oxide.

Continued . . .

(2) Assumes 0.9% $U_{235}$ in the spent fuel. Allowance is made for $U_{236}$ contamination, which will reduce the value of recovered uranium as enrichment feed by approximately 45% in the early 1980s.

(3) $Pu_f$ stands for fissile Pu. Fabrication cost penalty for MOX based on estimated 1975 quotes of U.S. commercial concerns of \$8/gm $Pu_f$, reported by S. Stoller, et al., *Report on Reprocessing and Recycle of Plutonium and Uranium--Task VII of the EEI Nuclear Fuels Supply Study Program*, Edison Electric Institute, December 30, 1975.

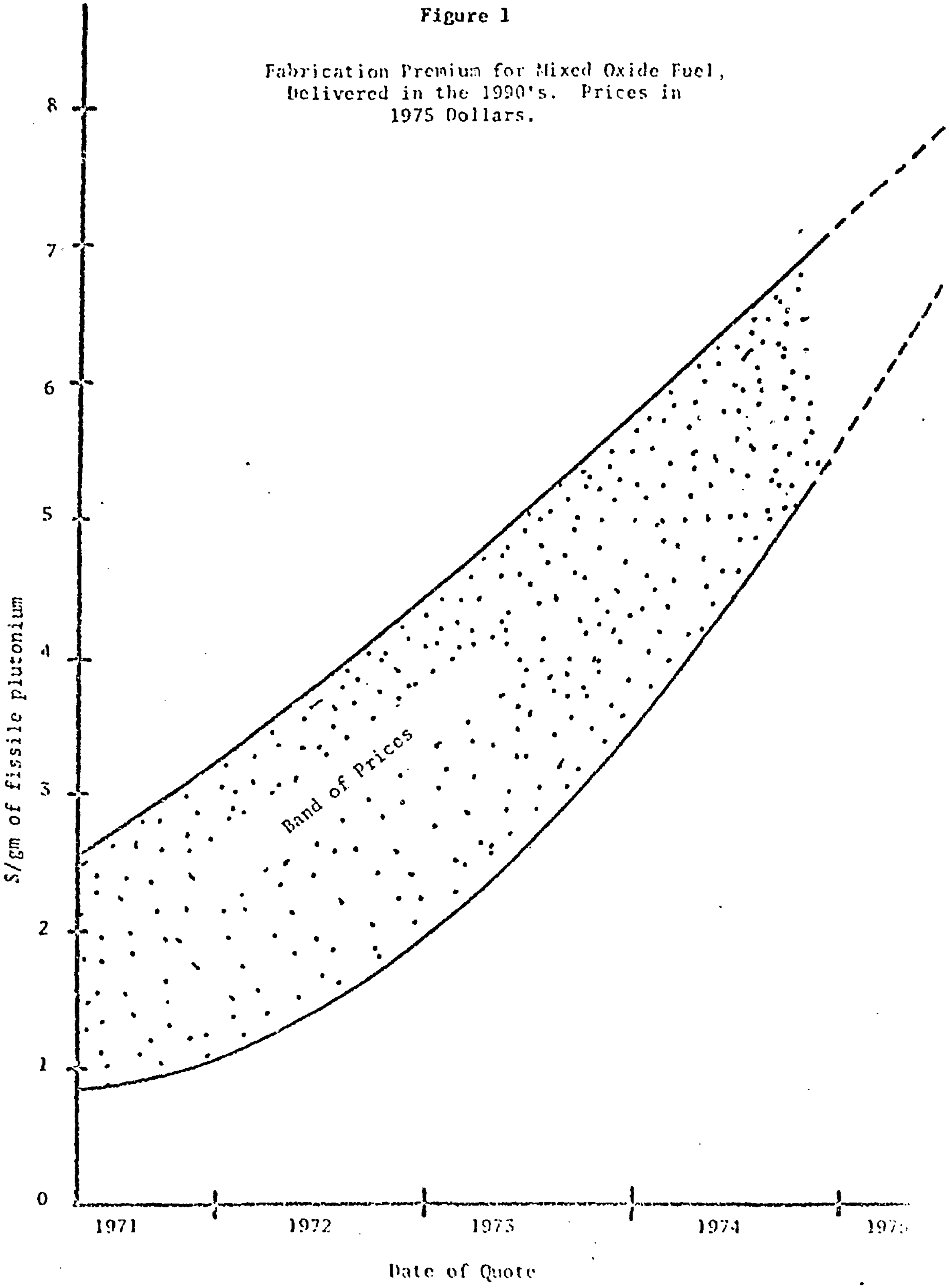
1. All of these prices lie well within the region of reasonable expectation; thus there is a substantial probability that reprocessing and recycling will prove uneconomic during this time frame.

2. No commercial reprocessing facilities are currently operating, and many serious uncertainties exist about their reliability and costs. Nor do commercial-scale MOX fabrication facilities exist. The general history of the nuclear field is that actual operations prove more difficult and expensive than drawing-board estimates. Reprocessing cost estimates have been rising rapidly, but most current estimates still do not fully include costs for waste management and solidification, nor for plutonium nitrate to oxide conversion facilities, nor for likely safeguard requirements. The estimate in Table 1 is based on our own analysis of likely costs at the U.S. Barnwell facility, if regulatory approval is given. It represents our best current estimate of likely costs; it is by no means an upper limit of what might occur.

3. The estimate of fabrication costs for MOX fuel draws upon data collected for a study done for the Edison Electric Institute. These data on quotes of U.S. commercial firms at various times (adjusted to 1975 dollars) are summarized in Figure 1. They show that quotes have been escalating very rapidly--at 35% per year (in constant dollars) from the beginning of 1971 through the end of 1974. If this rate of increase were to continue to 1983 (when recycle might begin in the U.S.) the MOX fabrication premium would be \$80 per gm $Pu_f$ (not the \$8 per gm assumed in Table 1), for a total fabrication cost of \$2,820 per kg.

## Figure 1

Fabrication Premium for Mixed Oxide Fuel, Delivered in the 1990's. Prices in 1975 Dollars.



Source: S. Stoller, et al., "Report on Reprocessing and Recycle of Plutonium and Uranium--Task VII of the EEI Nuclear Fuels Supply Study Program," Edison Electric Institute, December 30, 1975.

Even if the cost premium is \$15 per gm of $Pu_f$, the total cost of a kg of mixed-oxide fuel would be nearly \$2,000, or almost twice the estimated cost of $UO_2$ fuel.

4. For the above reasons, it seems unlikely that mixed-oxide fuels will be significantly less expensive than the estimate of Table 1. Thus, if recycle fuel is to be cheaper than virgin uranium fuel, this is most likely to occur if uranium or enrichment prices are higher than those assumed in Table 1. Although we believe the prices in Table 1 to be reasonable expectations for the early 1980s (in 1975 dollars), we readily admit they may be significantly higher. For uranium dioxide fuel to be 10% more expensive than MOX fuel would require prices of \$123 per SWU and \$123 per kg U (\$47 per lb $U_3O_8$), or a uranium price of \$134 per kg and a SWU price of \$100.

In evaluating the profitability of investment in recycle facilities, weight must also be given to the possibility that some prices may be lower than assumed in Table 1. To recover the capital investment in these facilities recycling must remain profitable over a 20-year period. If laser separation techniques are successfully developed within the next 10 years, separative work prices may decline dramatically.

5. Comparison of costs per kilogram of fuel implies that MOX fuel will perform as well as U-235 enriched fuel. There have been, however, recurring problems with U-235 fuel, and average performance is still well below design objectives. Given the greater difficulty of fabricating MOX fuel (a process that must be carried out automatically or in glove boxes because of the high toxicity of plutonium), there would appear to be substantial likelihood of lower average burnup for MOX fuels than for U-235 fuels. A 10% lower burnup would cancel a 10% per kilogram cost advantage.

## B. The Impact of Plutonium Recycle on Requirements for Ultimate Storage of Radioactive Materials

One of the prevailing fictions about reprocessing is that it will reduce the problem of ultimate storage of radioactive wastes. In fact, reprocessing combined with plutonium recycle will increase ultimate storage requirements: Each kilogram of mixed-oxide fuel will require at least 3 to 4 times as much high-level storage as the $UO_2$ fuel it replaces.

The greater waste storage requirements for mixed-oxide (MOX) fuel derive from the more energetic, slower-decaying radioactivity of spent mixed-oxide fuel as compared to spent $UO_2$ fuel. High-level waste storage requirements are essentially proportional to the heat output of the waste, which is in turn directly related to the radioactivity of the waste.* Thus the greater radioactivity of spent MOX fuel means greater storage requirements, and the magnitude of the added requirements is substantial.

### 1. Heat Output of Spent Fuel

In $UO_2$ spent fuel, the radioactivity is predominantly from fission products with relatively short half-lives; thus decay heat declines by 50% about every 2.24 years. Ten years after discharge, typical

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*There will be some costs that are related to volume, but the major costs will be related to removal of radioactive decay heat. As will be shown later, reprocessing and recycle also will generate a much larger total volume of waste than the alternative of direct disposal of spent fuel.

discharged PWR fuel will have a heat rate of 1080 watts per MTU.* Mixed oxide fuel contains, in addition to the fission products, substantial amounts of heat-producing Cm-244, which decays with a half-life of 16.2 years. Ten years after discharge, spent equilibrium-recycle MOX fuel will have a heat rate of 4200 watts, almost 4 times the comparable rate for $UO_2$ spent fuel.**

## 2. Ultimate Storage Costs for MOX

If ultimate high-level storage charges are based on thermal output, charges for this storage would be about 4 times as large for MOX as for $UO_2$ fuel (assuming transfer to ultimate storage 10 years after discharge).

A similar result is obtained if one assumes waste products are to be placed in standard storage containers and transferred to ultimate storage when $UO_2$ waste reaches an acceptable thermal output level. Based upon U.S. design studies, thermal output of a standard container (containing 6.28 cu ft of waste from 3.14 MTU of spent fuel) of $UO_2$ waste would decay in 6 years to 5 kilowatts (the maximum acceptable level in the design study). The same amount of MOX fuel waste would need to be placed in about 3 containers to meet the 5 kilowatt criterion.

In addition to the greater heat output of MOX fuel when initially transferred to ultimate storage (3 to 4 times greater than $UO_2$ fuel), the slower decay of MOX fuel means substantially greater long-term heat removal requirements. For example, one MTU of $UO_2$ wastes will generate only 185

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*Data in this section, unless otherwise specified, are from Chapter IV, Section H, of the draft Generic Environmental Mixed Oxide (GESMO) Fuel (Volume 3), WASH-1327, August 1974.

**Since neither uranium nor plutonium contribute significantly to heat generation, the waste storage requirements (on a heat-handling basis) are the same for an MTU of spent fuel whether stored directly or reprocessed first.

watts 20 years after discharge, but a similar quantity of MOX wastes will still be generating 2100 watts. In some designs for long-term storage, this greater continuing heat output would significantly affect total system costs. In such cases, the ultimate storage costs for MOX wastes would be still greater than the previously estimated 3-4 times the cost for $UO_2$ waste storage.

## 3. Volume of Wastes from Reprocessing as Compared to Direct Disposal of Fuel

Although the higher heat output of MOX fuel is unavoidable, a counter argument in favor of reprocessing is that it reduces the volume of high-level waste that needs special storage treatment. As has been pointed out, heat output is the primary factor determining storage costs for high level waste, but even the volume argument provides little support for reprocessing as a waste-management technique. Tables 2 and 3 show the volumes of waste per MTU of fuel reprocessed and the volume per MTU of fuel stored directly, without reprocessing. The total volume to be

## Table 2

## VOLUME OF RADIOACTIVE WASTE FROM REPROCESSING AND MOX FABRICATION[1]

| Reprocessing | Cu Ft per MTU of Spent Fuel Reprocessed |
|---|---|
| High level solidified waste | 3.0[2] |
| Intermediate level solidified waste | 3.3[2] |
| Fuel cladding | 16.7[2] |
| Process trash | 61.3 |
| Failed large process equipment | 8.0 |
| Subtotal | 92.3 |
| **Mixed Oxide Fabrication** | |
| Solidified scrap waste | .8[2] |
| Other solidified waste | .5[2] |
| Process trash | 2.4 |
| Failed large process equipment | .3 |
| Subtotal | 4.0 |
| TOTAL | 96.3 |
| TOTAL REQUIRING HIGH-LEVEL STORAGE | 24.3 |

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[1] Source: GESMO, Chapter IV, op. cit., and internal Science Applications, Inc., analyses.

[2] Materials requiring storage identical to high-level waste.

## Table 3

## VOLUME OF TYPICAL DIRECT STORAGE OF SPENT FUEL ELEMENTS[1]

| | |
|---|---|
| Volume of storage container (14' x 30"--zinc filled) | 55.3 $ft^3$ |
| Weight of contained fuel (4 PWR assemblies) | 1.76 MTU |
| Volume per MTU of spent fuel | 31.4 $ft^3$/MTU |

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[1] Source: Science Applications, Inc., internal analyses.

stored with reprocessing is about three times as large as the volume with direct storage, and note that all waste must be kept isolated for geologic time periods because of plutonium contamination.

Even restricting consideration to those materials requiring containment and storage identical to high-level waste, the storage volume with reprocessing is 75% of the direct-storage volume. Although this does represent some savings on a volume basis, it hardly seems significant when set against the three-to-four-fold greater heat output of MOX spent fuel wastes.

## C. Possible Recycle Savings in Perspective

Suppose, contrary to all reasonable expectations, that fuel cycle savings of 10% were possible per kg of MOX fuel. What would this mean to the overall economics of nuclear-generated electricity? Nuclear reactors that start operation in the early 1980s will likely cost around $1,000 (1975 dollars) per kilowatt of capacity. Operating at 60% of capacity and at a fixed charge rate of 15%, the capital costs per kwh will equal 28 mills ($.028) per kwh. Operating and maintenance costs will total, perhaps, 3 mills per kwh; thus, non-fuel costs will equal about 31 mills per kwh. Fuel costs will, of course, depend upon uranium and enrichment costs. Consider $UO_2$ fuel costs of $1,450 per kg, the figure corresponding to a 10% cost advantage for the mixed-oxide fuel costs in the example of Table 1. In Table 4, these costs are translated into per kwh fuel costs and added to the estimated non-fuel cost of 31 mills per kwh.

## Table 4

## HYPOTHETICAL NUCLEAR ELECTRICITY COSTS IN THE EARLY 1980s
(Prices in 1975 dollars)

| | $UO_2$ Fuel at $1450 per kg (mills) | MOX Fuel at $1320 per kg (mills) |
|---|---|---|
| Fuel Costs per Kwh | | |
| Cost of fuel consumed[1] | 6.1 | 5.6 |
| Interest cost on fuel core[2] | 1.1 | 1.0 |
| Total fuel costs | 7.2 | 6.6 |
| Non-Fuel Costs per Kwh | | |
| Capital costs | 28 | 28 |
| Operating and maintenance costs | 3 | 3 |
| | 31 | 31 |
| Total generating costs per kwh | 38.2 | 37.6 |

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[1] Assumes thermal efficiency of .33 and burnup of 30,000 $MWD_{th}$/MTU, appropriate for a replacement load in a PWR.

[2] Assumes a core load of 80 kg of fuel per kw of capacity (typical for a PWR), a 10% carrying charge, 60% capacity factor, and an average in-core fuel value equal to one-half the value of new fuel.

The assumed MOX fuel savings of 10% lower total generating costs by 0.6 mills, or 1.6%. But, generating costs are only about 50% of delivered electricity costs; therefore, the 10% fuel saving would translate into a 0.8% reduction in the cost of delivered electricity. Further, however, even if recycle is pursued to the maximum possible extent, MOX fuel could provide only about 10% of total nuclear fuel requirements;* thus the 10% cost advantage for MOX fuel would reduce total system nuclear electricity costs by 10% of 0.8% or about one-tenth of one percent.

In adopting plutonium recycle, we would be risking the spread of nuclear weapons to tens of additional countries for the sake of <u>possible</u> monetary savings that would be offset by a few months of capital-cost inflation at recent rates. The word "<u>possible</u>" is stressed because it seems far more likely that early adoption of plutonium recycle will result in net economic losses than in net economic gains. Plutonium recycle will only be profitable at very high uranium prices, but the analysis presented in later sections strongly suggests that uranium prices will be quite moderate in the 1980s.

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*See Chapter III, which shows that for the growth rates projected for nuclear power, recycled products will supply less than 20% of fissile-fuel needs. About one-half of the recycle fuel is MOX, the rest is recovered uranium In calculating the cost of MOX fuel, credit was given for the recovered um; thus the (less than 10%) of fuel requirements met by MOX fuel reflect the al monetary savings possible from recycle.

## III. Recycling and Resource Conservation

Proponents of recycling often couch their arguments primarily in terms of natural resource savings. A number of points need to be made about such arguments:

1. Recycling is not the only means of conserving uranium resources. Most importantly, perhaps, enrichment can be substituted for uranium in LWR's. In the U.S., current ERDA planning envisions operation of its enrichment facilities in the 1980's at a tails assay of 0.37% U-235 in the event plutonium recycle is not permitted. Under this plan, more than half of the U-235 in natural uranium would end up in the waste stream. By lowering the tails assay to 0.2% from 0.37% U-235 (a change which would lower total fuel costs at present prices), ERDA could reduce uranium requirements by 33%. This is a substantially greater saving of uranium than could be achieved by recycling.

If uranium saving is to be given a very high priority, tails assays even lower than 0.2% could be used, although the costs begin to rise. If further savings are to be sought, perhaps consideration should be given to shifting emphasis from LWR technology to HWR technology of the CANDU type. As compared to LWR's (with fuel enriched at 0.2% tails), CANDU's use about 27% less uranium. Again, this is a greater saving than is realistically possible through reprocessing and recycle.

2. Also, there are non-nuclear alternatives for generating electricity, and if one is concerned specifically with natural resources, substituting coal for uranium would seem sensible, since coal is far more abundant. For example, if economically recoverable uranium in the world amounts to $10 \times 10^6$ tons $U_3O_8$ (a higher amount than most current estimates), the

electrical energy equivalent of this uranium if used in LWR's is about 2% to 3% of estimated world minable coal resources.* Thus a fraction of one-percent of the world's coal resources would substitute for potential recycle savings of 20% of the world's uranium resources.

3. In evaluating energy resource conservation, one should consider total energy resources -- not simply one element in isolation. Considered from this viewpoint, recycling of spent nuclear fuel is of minor consequence. By 1990, nuclear power might (optimistically) satisfy 10% of U.S. energy requirements; thus reducing the energy resource input to nuclear power by 20% would reduce <u>total</u> energy resource requirements by only 2%. Put another way, implementing recycling would take care of less than one-year's growth in U.S. energy requirements. Since the rest of the world consumes relatively less of its energy in electrical form, savings from recycle would be even less in other countries.

4. Finally, many estimates of potential savings from recycling are greatly exaggerated. Exaggeration can arise in a number of ways:

a) Recovered uranium is contaminated with U-236, which significantly reduces its value. As compared to uncontaminated uranium, recovered uranium is worth only about 50%-60% as much, whether used as feed to gaseous diffusion enrichment facilities or as a base for mixed-oxide fuel (this last can utilize only about 20% of recovered uranium in any event). Mixing recovered uranium with over-enriched natural uranium is sometimes suggested as a means of reducing the U-236 penalty--but in fact, it increases

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*M. King Hubbert, "Energy Resources," in <u>Resources and Man</u>, W. H. Freeman and Sons, San Francisco, 1969, p. 203. Hubbert gives an estimate of $4.3 - 7.6 \times 10^{12}$ metric tons of minable coal. Ten million tons of $U_3O_8$ are equivalent to about $12.5 \times 10^{10}$ metric tons of coal if used in LWR's.

the economic penalty from U-236 to such an extent that recovered uranium is likely to have no value if employed in this way.*

Most calculations of recycle savings either ignore the U-236 effect or treat it as an "uncertainty," but there is no controversy over its existence. The only means of reducing its impact from the 40% to 50% level is to re-enrich recovered uranium in a dedicated facility. No such facility now exists or is planned. Until such a plant is made a part of reprocessing plans, calculations should be based on the full penalty. In the event such a plant is built, the economic penalty could be reduced but would still amount to about 25% of the uncontaminated value.

b) The initial fuel load and first several reloads, to which recycle can make no contribution, are often ignored in calculating percentage savings in uranium requirements.

c) Recycle savings are often calculated in a hypothetical "steady-state," in which the number of reactors is fixed. In the real world, the number is growing rapidly, and the faster the rate of growth, the smaller the percentage resource savings possible from recycle.

When all of the facts mentioned above are taken into account, the calculated resource savings from recycle turn out to be quite small. Table 5 shows several recent estimates of cumulative uranium savings from recycle through the year 2000. With both uranium and plutonium recycle, calculated savings are from 12% - 16% of total requirements. Although

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* Vincent Taylor, "The Effect of U-236 on the Resource Value of Recovered Uranium," unpublished paper, Pan Heuristics, April 23, 1976.

Table 5

## Estimated Potential Resource Savings to the Year 2000
## From Recycle of Plutonium and Uranium

| Source of Estimate | For Year | Type | Percent Uranium Savings from Recycle |
|---|---|---|---|
| Edison Electric Institute[1] | 2000 | Non-Communist $U_3O_8$ Requirements-Cumulative | 16% |
| NEA-IAEA[2] | 2000 | Non-Communist $U_3O_8$ Requirements-Cumulative (Pu Recycle Savings Only) | 6% |
| NEA-IAEA-Author | 2000 | Non-Communist $U_3O_8$ Requirements-Cumulative | 12% |

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1. Edison Electric Nuclear Fuels Supply Program, Task II, prepared by J. Steyn and R. Fell, Resource Analysis Corp., December 1975, Table 1.2.3. It is not clear whether the U-236 penalty has been included in this estimate. If not, the uranium savings from recycle amount to about 12%.

2. Uranium Resources Production, and Demand, Joint Report of OECD Nuclear Energy Agency, and the IAEA, December 1975.

3. NEA-IAEA estimate revised by author to include uranium savings from uranium recycle (estimated to equal the savings from plutonium recycle).

such savings are significant, they are far too small to justify terming recycling an "essential resource conservation measure," as have some proponents. And, as has been pointed out previously, in total resources, recycling seems likely to consume more than it saves -- thus, perhaps recycling ought more appropriately be termed an "avoidable resource consumption measure."

# IV. The Need for Realistic Projections of Nuclear Power Growth: The Implications for Investment in Recycling and Breeder Development

## A. Introduction

A careful review of official forecasts of nuclear power growth in Europe, the U.S., and Japan reveals that all of them are greatly exaggerated. They appear to represent the dreams of the nuclear proponents rather than a realistic assessment of actual prospects. Considerations of more realistic rates of nuclear-power growth reveal that the haunting spectre of imminent uranium shortage is only a part of the dream. In fact, with realistic growth expectations, there is unquestionably sufficient low-cost uranium to allow use of LWR technology well into the next century. With this favorable supply-demand outlook for uranium, there is no need for early pursuit of recycle, and breeder development can proceed at a slower, more economical pace.

Special Note: The next part of this section surveys the evidence on electricity growth in Europe and examines the implications of projections based on this evidence. The original intention was to follow this with a similar analysis of the U.S. and a more limited survey of prospects in Japan. There was not enough time to get these latter parts in shape for inclusion, but the analyses for the U.S. and Japan were completed to the point where they gave high assurance that official forecasts in these countries are at least as much in error as those in Europe.

## B. Projected Growth of Electricity Consumption and Generating Capacity in Europe

European countries are attempting to satisfy most of the growth in electricity demand by adding nuclear generating capacity. According to recent official forecasts by individual countries, annual electricity consumption in the European Community (EC) is expected to increase by about $1{,}000 \times 10^9$ kwh or 91% between 1975 and 1985; of this increase, about $800 \times 10^9$ kwh are projected to be supplied by nuclear power.* Obviously, then, the growth in total electricity consumption will have an important influence on additions to nuclear capacity.

How realistic is the projected growth in electricity consumption? To answer this question, it is helpful to look at the past relation between growth in electricity consumption and growth in the volume of Gross Domestic Product (GDP). The data displayed in Figure 2 shows a good fit for the relations:

$$(1) \quad \frac{\Delta E}{E} = .03/\text{year} + .86\frac{\Delta GDP}{GDP},$$

for the period 1964-1973, where E is electricity consumption and GDP is real Gross Domestic Product for the original six members of the European Community.**

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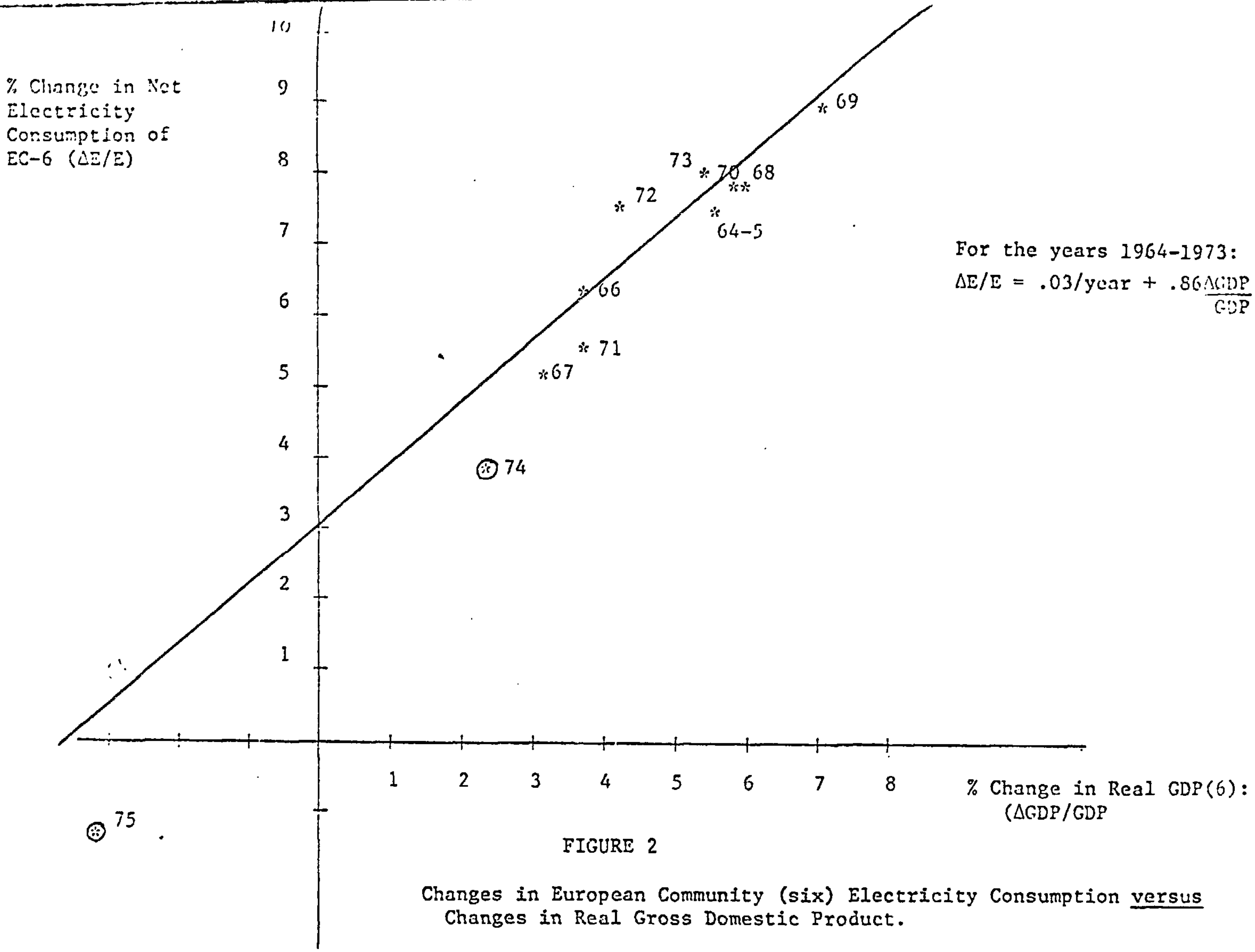
* Report of the Achievement of the Community Policy Objectives for 1985, Commission of the European Communities, Com (76)9, Brussels, 16 January 1976, Annex, p. 19.

**France, Germany and Italy are the important countries in Eur-6, and also the countries planning major expansions of nuclear power. Great Britain has only modest nuclear expansion plans. The data points for 1974 and 1975 lie below the line fitted through the points for earlier years.



For the years 1964-1973:

$\Delta E/E = .03/\text{year} + .86\frac{\Delta GDP}{GDP}$

FIGURE 2

Changes in European Community (six) Electricity Consumption versus Changes in Real Gross Domestic Product.

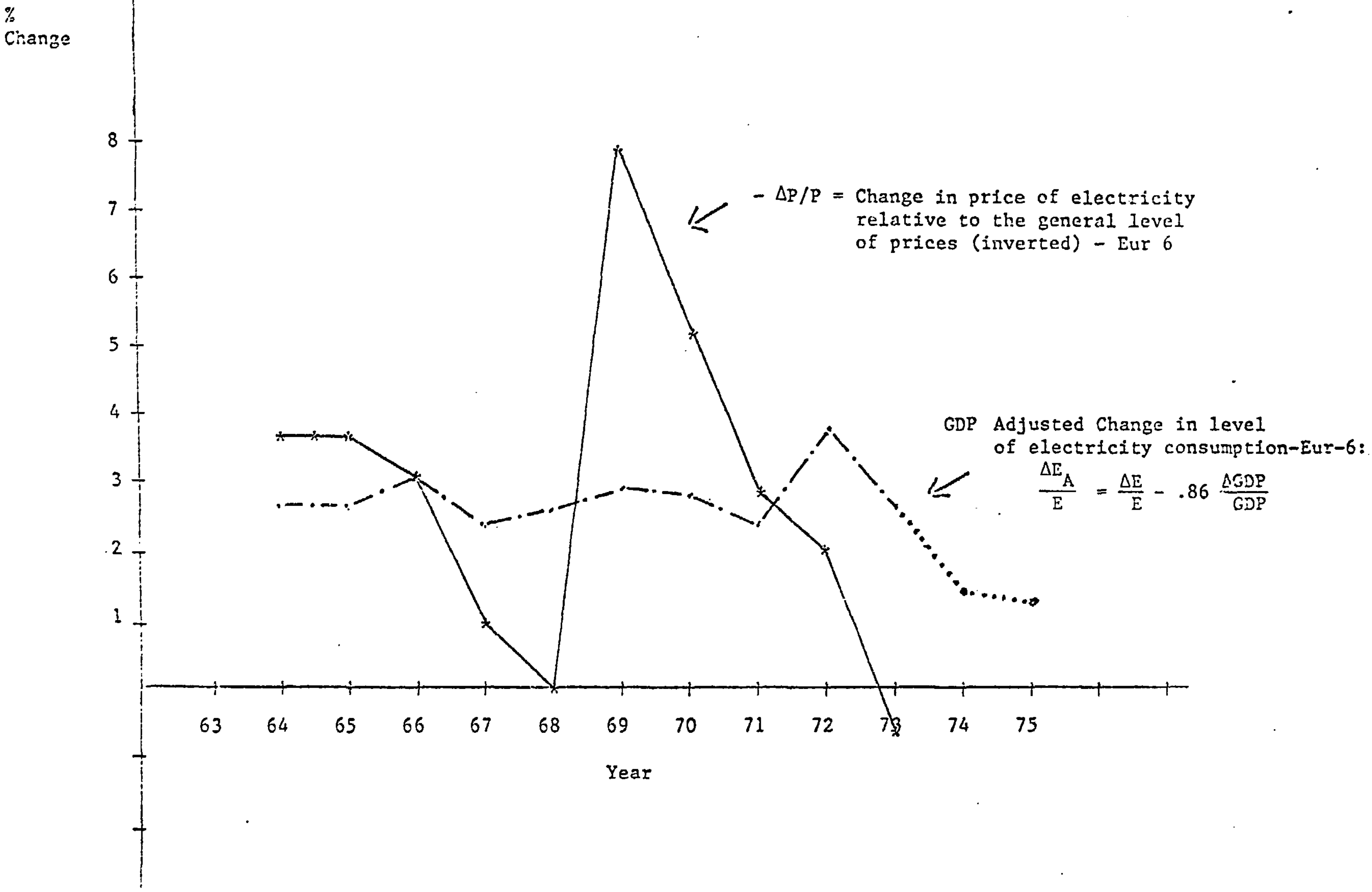
Of crucial importance in predicting future growth in electricity consumption is the size of the intercept, that is the growth that is unrelated to changes in GDP. For the 1964-1973 period, the intercept value for the EC was (as shown in Figure 2) 3 percent per year. Analytical studies on electricity demand all show an elasticity of demand with respect to the real price of about -1 (implying a percentage change in demand equal and opposite to the percentage change in price) over the long run. Thus, it is natural to assume that the intercept largely reflects the declining price of electricity (in real terms) in Europe during this period. And, in fact, the average rate of decline in real electricity prices in the period 1964-1973 was 3 percent per year, which would yield the 1964-73 intercept for electricity growth (+3 percent per year) given a price elasticity of -1.0.

Although the above analysis makes it plausible to attribute the intercept to price changes, no confirmation for this conclusion can be found in the data on annual changes. Figure 3 shows electricity consumption changes (adjusted for changes in GDP) and real price changes for the period 1964-1973. No significant correlation exists on a year to year basis between the two sets of changes. Changes in adjusted consumption remained nearly constant at 3% per year, while price declines varied in a horizontal S pattern.

Figure 3 shows that GDP adjusted changes in consumption of electricity did drop (to about 1.5% per year) in 1974 and 1975. The declines in GDP-adjusted electricity consumption in 1974 and 1975 are very suggestive that future electricity growth will fall below past experience. In the future, electricity prices seem certain to rise relative to general prices (or at best stay even with them) in contrast

Figure 3

Relation Between Electricity Price Changes and Changes in the GDP-Adjusted Consumption of Electricity Over Time-European Community (6)



to past experience of declining relative prices. In itself, the price behavior of electricity would imply substantially lower future electricity growth. There is, however, the question of the extent to which electricity will be substituted for direct consumption of fossil fuels. There is a desire in Europe to see less dependence on fossil fuels and, thus, shifts toward nuclear-produced electricity are being encouraged in some countries. Such shifts will work against the direct price effects, and the question is to what extent they will offset these effects.

The period 1973-1974 saw the sharpest rise in fossil-fuel prices relative to electricity prices that we are likely to see in this century. Yet, in spite of this great shift in relative prices, GDP-adjusted electricity consumption declined in 1974 and 1975. Granted that the effects are not fully worked out, this still lends strong support to a lower-growth forecast. Further, for at least the next five to ten years, installation of new, higher-cost generating capacity seems quite likely to cause electricity prices to rise more than fossile fuel pri

Although future growth is highly uncertain, the currently a evidence points to lower growth than in the past. To explore the implications of lower growth, I have projected electricity demand assuming two different intercept values (electricity growth rates for zero change in GDP) in equation (1): 2.5% and 0% per year.

The highest of the intercepts, 2.5% per year, is just slightly less than the experience of 1964-73, which was highly favorable for electricity growth, and about 1% greater than the 1974-75 intercept.

This would seem to be a likely upper limit for the intercept-growth rate over the next 10-15 years. The zero-intercept assumption implies no further growth of electricity other than that induced by general economic growth. It is, in a sense, a neutral assumption about the future prospects for electricity growth--implying neither extensive electricity conservation nor a continuation of the trends of previous decades. This would seem to be a case that deserves serious consideration in national planning.

The states of the European Community are currently projecting 3.0%-3.5% per year increases in GDP from 1975 to 1985. Applying equation (1) to the upper estimate yields GDP-related electricity growth of 3% per year (.86 x 3.5% per year). Adding this to the two intercept values yields a high-growth estimate of 5.5% per year and a moderate growth estimate of 3% per year. These two growth rates are used to make alternative projections of total electricity demand in 1985 and 1990. The results are shown in Table 6. Table 6 also lists the total generating capacity required to meet these projected demands and the amount of this capacity that would be nuclear, assuming realization of the EC forecast that 80% of thermal additions will be nuclear.

Table 6 also lists official forecasts for 1985 and 1995. These forecasts are far above even the high-growth projections: For 1985, official estimates of nuclear capacity are 50% higher than the high-growth projection and, following a common pattern in the nuclear field, the official estimates for 1990 are even less plausible--exceeding the high-growth projection by 80% to 200%.

Table 6

# PROJECTED ELECTRICITY GROWTH
# AND
# GENERATING CAPACITY IN THE EUROPEAN COMMUNITY: 1985 and 1990

| | 1975 | 1985 | | | 1990 | | |
|---|---|---|---|---|---|---|---|
| | | High | Mod | Official | High | Mod | Official |
| Electricity Consumption (net) Kwhx$10^9$ | 981(1) | 1676 | 1318 | 2065(3) | 2039 | 1528 | 3650 |
| Installed Generating Capacity (GW) | | | | | | | |
| Total | 281(2) | 415 | 354 | 501 | 490 | 392 | 753(5) |
| Nuclear | 13(3) | 107 | 58 | 156(3) | 162 | 84 | 292(4)<br>412(5) |
| Conventional Thermal | 223(2) | 247 | 235 | 284 | 260 | 240 | 273(5) |
| Hydro | 45(2) | 61(2) | 61(2) | 61(2) | 68(2) | 68(2) | 68(2) |

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General: High projections assume 5.5%/year growth in electricity consumption, moderate projections assume 3%/year growth. Capacity utilization factors are from reference cited in Note (2), except conventional thermal plants are assumed to continue to be used 4,100 hrs/year through 1990. Eighty percent of all thermal plant additions are assumed to be nuclear.

[1] Eurostat Statistical Bulletin 16-2-76

[2] Guideline for the Electricity Sector, Commission of the European Communities, Com(74) 1970 final, Brussels, 27 November 1974, Annex, 2nd part, from table titled "Development of the Pattern of Production Capacities;" 1975 estimates adjusted for decrease in actual installed nuclear capacity in 1975. Hydro and thermal estimates as per table.

[3] Report of the Achievement or the Community Energy Policy Objective for 1985, Commission of the European Communities, Com (76)9, Brussels, 16 January 1976, pp. 15, 19.

[4] Estimate of the NEA/IAEA Working Group, Dec. 1975, reported in "Prospects for the World Nuclear Energy Market," Nuclear Engineering International, April/May 1976, Table 2, p. 92, based on official government estimates.

[5] European Community target figures for 1990, as cited in the report referenced in Note (2).

In Europe, as in the United States, the official estimates of nuclear power growth are based on highly inflated projections of future electricity consumption. Using more plausible projections, one obtains estimates of installed nuclear capacity (assuming nuclear power is highly favored for additional capacity) that are 30% to 65% less than official estimates for 1985, and even smaller fractions of official estimates for 1990.

## C. Uranium Resource Requirements and Supplies

When nuclear forecasts are deflated toward reality, the spectre of uranium scarcity recedes well into the future. As the previous section indicated, reasonable estimates for nuclear capacity in 1990 in the OECD are only one-half to one-third of official estimates. An analysis of the United States (to be reported elsewhere) shows similar results, with a high-estimate of installed nuclear capacity in 1990 of about 170 GW. This can be compared with the recent NEA-IAEA forecast of 385 GW for the U.S. in 1990.

A country-by-country analysis would show that official estimates, such as those by the NEA-IAEA working group, uniformly overestimate electricity demand and underestimate the obstacles to rapid nuclear growth. As a basis for planning, such gross overestimates have led to many bad decisions. In particular, they have created an illusory uranium shortage that is being used to justify large investments in breeder technology, reprocessing, and recycling.

Generally, the further into the future that projections are carried, the less they are bound by current realities, and the more fanciful they become. Thus, while the NEA-IAEA estimates of nuclear capacity for 1985 are probably high by a factor of two, their estimates for the year 2000 may well be high by a factor of four. They estimate non-Communist world installed capacity of 2,480 GW in 2000--compared to only 69 GW in 1975. The political acceptability of such rapid installation of so many reactors seems very questionable, given the evident public opposition to the much more modest current programs. Further, electricity growth will fall well below the growth rates of 6% to 7% implicit in these forecasts.

The implications of more moderate growth are tabulated in Table 7. Here the installed nuclear capacity in 2000 is assumed to total 1000 GW with a uniform growth rate of about 11.3% per year throughout the period--a rate that is on the high side of what seems likely on present evidence.

The cumulative uranium requirements to 2000, assuming end-year capacity of 1000 GW are about 1.9 million tons $U_3O_8$. By comparison, the NEA-IAEA estimate of 2480 GW of capacity by 2000 implies $U_3O_8$ requirements to that time of 3.8 million tons.

The implications of these two estimates of uranium requirements are vastly different: On the low estimate, the world has a comfortable margin of uranium resources to carry it well into the 21st century. On the high estimate, we are coming close by 2000 to exhausting uranium resources currently identified as either reserves or probable additions to reserves.

Table 8 shows a recent compilation of assured plus probable reserves at under \$30 per lb $U_3O_8$. The total is 4.9 million tons $U_3O_8$. This

## Table 7

## PROJECTED URANIUM REQUIREMENTS
## TO THE YEAR 2000

| Forecast Nuclear Capacity (GW) | Cumulative Uranium Requirements[1] ($10^3 STU_3O_8$) | Estimated Probable Low-Cost Uranium Resources[2] ($10^3 STU_3O_8$) | Annual Uranium Requirements ($10^3 STU_3O_8$) |
|---|---|---|---|
| 1000 | 1,969 | 4,900 | 224 |
| 2480[3] | 3,826 | 4,900 | 313 |

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[1] Assumes no recycle and .2% tails for the 1000 GW capacity figure and no recycle and .25% tails for the 2480 GW capacity figure.

[2] See Table 8 for source of estimate.

[3] The high estimate as reported in Uranium Resources, Production, and Demand, joint report of the OECD Nuclear Energy Agency and the IAEA, December, 1975.

is a comfortable margin over the 1.9 million ton consumption estimate, but much less reassuring compared to the estimate of 3.8 million tons.

The different implications of high and moderate growth remain when one considers more speculative estimates of uranium resources. A recent survey of uranium resource estimates undertaken by Pan Heuristics makes a plausible case that recoverable world-wide uranium resources total at least 10-20 million tons.* If correct, the need for the breeder and other uranium-extending measures such as recycling recede very far into the 21st century under moderate growth assumptions. But, with the high growth assumptions of NEA-IAEA, which imply a doubling of nuclear capacity each decade near the end of the century, even 20 million tons of $U_3O_8$ could be consumed within the first few decades of the 21st century.

## D. Conclusion

Both common sense and all available evidence indicate that nuclear power will grow far more slowly than the forecasts of the nuclear advocates--forecasts which currently appear to dominate policy discussions. More moderate (but still high) projections of nuclear growth indicate that there are ample uranium resources to take us well into the next century. There is no need for an early decision to undertake recycling, and research on breeder development can proceed at a slower, more economical rate.

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*D. Gaskins, "Estimates of the Supply of Uranium," Pan Heuristics, May 1976, unpublished.

Table 8

## WORLD SUPPLY OF URANIUM
1000 Tons $U_3O_8$

| | Reasonably Assured Resources | | Estimate Probable Additional Resources[1] | |
|---|---|---|---|---|
| | <\$15/lb. $U_3O_8$ | \$15-30/lb. $U_3O_8$ | <\$15/lb. $U_3O_8$ | \$15-30/lb. $U_3O_8$ |
| Africa | 368.8 | 130.0 | 53.0 | 107.9 |
| Algeria | 36.4 | ---- | ---- | ---- |
| C.A.R. | 10.4 | ---- | 10.4 | ---- |
| Gabon | 26.0 | ---- | 6.5 | 6.5 |
| Niger | 52.0 | 13.0 | 26.0 | 13.0 |
| South Africa | 241.8 | 117.0 | 7.8 | 88.4 |
| Zaire | 2.2 | ---- | 2.3 | ---- |
| Asia | 9.2 | 45.8 | 1.5 | 29.2 |
| India | 4.4 | 33.5 | 1.0 | 29.2 |
| Japan | 1.4 | 8.6 | --- | ---- |
| Korea | --- | 3.1 | --- | ---- |
| Turkey | 3.4 | .6 | .5 | ---- |
| Australia | 476.0 | --- | 104.0 | ---- |
| North America | 763.7 | 239.9 | 1076.2 | 528.5 |
| Canada | 187.2 | 28.6 | 421.2 | 123.5 |
| Mexico | 6.5 | 1.3 | --- | ---- |
| U.S. | 570.0 | 210.0 | 655.0 | 405.0 |
| South America | 24.7 | 15.6 | 30.9 | 31.2 |
| Argentina | 12.1 | 14.7 | 19.5 | 31.2 |
| Brazil | 12.6 | .9 | 11.4 | --- |
| Western Europe | 76.2 | 552.8 | 45.2 | 190.1 |
| Finland | ----- | 2.5 | ---- | ---- |
| France | 48.1 | 23.4 | 32.5 | 19.5 |
| Germany | .6 | .6 | 1.3 | 3.9 |
| Greenland | ---- | 7.8 | ---- | 13.0 |
| Italy | ---- | 1.6 | ---- | 1.3 |
| Portugal | 9.0 | ---- | ---- | ---- |
| Spain | 13.0 | 121.6 | 11.4 | 127.4 |
| Sweden | ---- | 390.0 | ---- | ---- |
| U.K. | ---- | 2.3 | ---- | ---- |
| Yugoslavia | 5.5 | 3.0 | ---- | 19.8 |
| World | 1718.6 | 984.1 | 1310.8 | 886.9 |

World Total in all above categories: 4.9 million tons $U_3O_8$

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Source: D. Gaskins, "Estimates of the Supply of Uranium," Pan Heuristics, Unpublished.

[1] Estimated to exist in extensions of known deposits or anticipated but undiscovered deposits in known uranium districts. Potential resources in the U.S. categories of possible or speculative are not included.

There are great uncertainties about all aspects of future energy consumption and production. In the face of such uncertainties, there are substantial benefits to be gained by deferring commitments and investments until more is known about the probable course of events. The clear message of this paper is that the costs of deferring commitments to recycle are likely to be minor relative to the potential benefits. Unless growth proceeds much faster than seems likely on the evidence at hand, present investments in these nuclear activities will be costly and wasteful. The prudent and rational course is to defer investments in these activities until such time as the course of actual events (rather than fanciful projections) profide reasonable assurance that they are needed.