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The fear of dependence on insecure or inadequate sources of fuel is having an important influence on the development of the nuclear industry around the world. As a result of concern about the supply of uranium and fuel processing services, many nations are more anxious than ever to gain access to nuclear fuel processing technology, including uranium enrichment and spent-fuel reprocessing. In this way they hope to loosen their ties to foreign suppliers. Moreover, the fear of dependence contributes to the push for the breeder reactor, which has a drastically reduced requirement for uranium fuel.

Unhappily, both of these responses to energy supply problems have a significant spillover in another area of international concern--nuclear weapons proliferation. For the fuel cycle facilities are a possible source of weapons-grade uranium and plutonium, and the advent of the breeder would require a large supply of plutonium. Of course, the proliferation problem would exist quite apart from these influences, but the fear of dependence makes matters worse.

Much of the insecurity is the result of expectations that the world's reactor population will grow very rapidly in relation to known uranium supplies, and is heightened by events suggesting a wavering supply from the established nuclear industry, particularly in the U.S. But over the past year to 18 months, conditions have been changing significantly. Though official recognition of the fact is slow to come, fuel supply prospects are now much less worrisome than they seemed only recently. Accordingly, opportunities now exist, through the establishment of stockpiles and other measures, to increase confidence in the security of the international fuel cycle, and thus to lower the pressures that seem to be leading to increased proliferation. However, there are costs and complex problems of management that must be faced if these opportunities are to be grasped.

Aspects of "Dependence"

All nations rely on international trade for supplies of critical goods and services. Thus one does not normally speak of "dependence" in a pejorative sense unless there is a threat that supplies may be cut off, or made available only at unacceptable cost. Yet in the case of reactor fuel, expressions of concern about dependence are common.

The Fuel Cycle. The system supplying light water reactors with fuel is shown on page 3; the solid arrows indicate the flow of materials in the current U.S. nuclear program. The system operates as follows: once uranium resources have been found and proven economic to exploit, mines and mills are built. The mills produce uranium oxide (U_3O_8) which goes to the enrichment process, for in its natural state, uranium contains only 0.711 per cent of the fissile isotope U^{235} (the rest being U^{238}). The fuel for the current **population** of light-water reactors requires a 2.7 to 3.2 per cent concentration depending on the reactor's design. Uranium enriched to around 3 per cent U^{235} is not suitable for weapons. However, the plants that enrich to 3 per cent can achieve much higher percentages if suitably modified (indeed, most current enrichment plants were built as part of weapons programs).

The 3-per-cent (or "low enriched") uranium is fabricated into fuel rods in a step not shown in the illustration, and fed into reactors. Spent rods are now held in temporary storage at the reactor site.

Along with a number of other fission byproducts, the spent fuel rods contain some residual U^{235}, and a new element created in the fission process--plutonium. By means of chemical separation, the uranium can be extracted, sent back through the enrichment step, and placed again in a

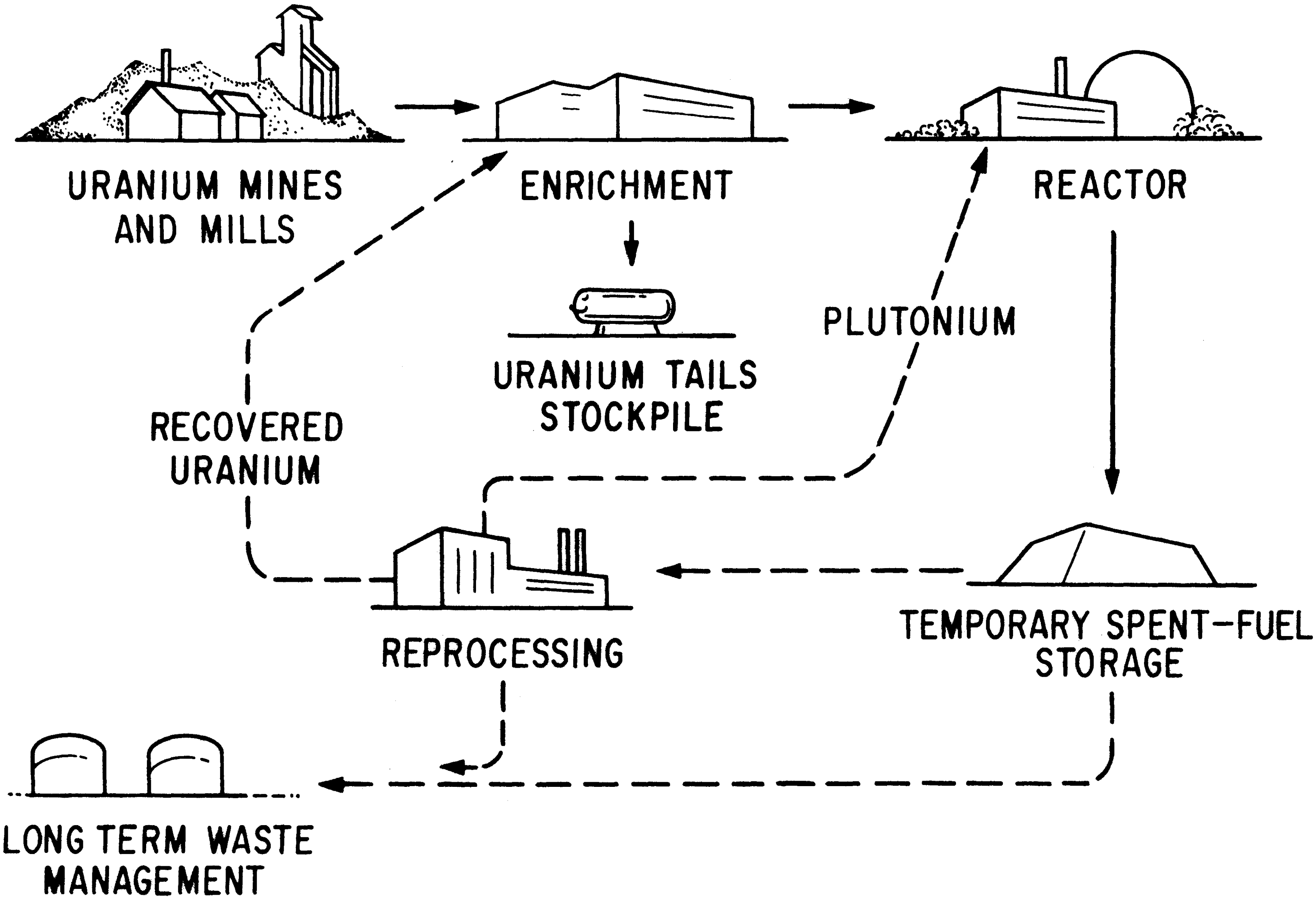

FIGURE 1. FUEL CYCLE FOR LIGHT WATER REACTORS

power reactor. So, too, can the plutonium be extracted. Plutonium, like U^{235}, is a fissile material, and can be fabricated with U^{235} into new fuel rods, in which case the rod is usually referred to as containing "mixed-oxide fuel." The plutonium extracted by the chemical separation process is suitable for weapons.

As indicated by the dashed lines in the illustration, fuel-rod reprocessing is not in use on a commercial basis in the U.S. Whether it should ever be is a matter of active dispute and discussion. One complicating aspect of the debate is the fact that plutonium is a necessary element in our current design of the breeder reactor: the breeder is designed to produce large quantities of plutonium from U^{238} fed in to it (recall that U^{238} constitutes the bulk of naturally-occurring uranium). The capital costs of the breeder are higher than those for the light-water reactor, but the requirements for uranium fuel are drastically reduced.

As part of his overall energy program, the President has declared that the U.S. will defer indefinitely the recycling of spent fuels in U.S. power plants. Moreover, the commercial demonstration of a breeder reactor has been delayed indefinitely, and R and D funds are being redirected from the plutonium breeder to other types of nuclear systems which, hopefully, might prove less of a proliferation risk. Administration policy appears to follow very closely the recommendations of a Ford Foundation Nuclear Energy Policy Study Group, Nuclear Power Issues and Choices (Ballinger, 1977). Whether other nations will follow suit is problematical.

The Status of Uranium Supply. The table on page 5 shows the major sources of uranium today and in the near future, along with a rough indication of estimated resources at a cost of \$66 per kilogram (\$30 per pound) of U_3O_8.

Table 1. World Natural Uranium Production Capabilities, and Current Estimates of Resources (USSR and China Are Excluded)

Country	Annual Production Capability[a] ($MT\ U_3O_8$)		Resources[b] ($10^3\ MT\ U_3O_8$)	
	Current	Attainable 1978	Reasonably Assured	Estimated Additional
United States	16,300	22,400	578	967
Australia	--	2,360	389	94
Sweden	--	--	354	--
So. & S.W. Africa	4,480	13,000	330	--
Canada	7,660	10,000	200	719
Argentina	191	608	342	366
France	2,120	2,590		
Gabon	708	1,420		
Germany	290	290		
Japan	36	36		
Mexico	--	290		
Niger	1,769	1,770		
Portugal	109	127		
Spain	172	399		
Yugoslavia	--	272		
Other	--	--		
Total:	33,800	55,600	2,190	2,150

Notes:

(a) Edison Electric Institute, Nuclear Fuels Supply, March 1976.

(b) R.D. Nininger, "Uranium Availability," presented at the International Conference of the Atomic Industrial Forum, November 17, 1976.

As the table shows, the U.S., Canada, Australia, and South Africa now dominate, though there is considerable uncertainty as to their relative roles in the future.

In Canada and Australia policy changes have been made in recent years, and large blocks of reserves have been removed from the international market. In Australia, new export commitments have been forbidden for some years, pending the resolution of a host of issues including public-private ownership, environmental problems, the role of foreign capital, and the desire to enrich uranium domestically as opposed to simply exporting it. In Canada, exporters can now draw only upon a margin of proved reserves beyond the total uranium needs for a full 30-year life of all Canadian reactors (existing, committed, or planned) to be installed over the next ten years. Given the long time horizons for exploration and the development of mines and mills, these provisions effectively remove Canada from the world market, at least for the next few years.

A portion of known and potential uranium resources is also found in less developed countries. In some cases export supplies are insecure due to inherent political instability; in others the problems are akin to those of Australia, where internal issues of equity, environment, and economic growth are yet to be resolved.

As a result of all these uncertainties, many consumer nations fear that uranium trade simply will not evolve a market pattern similar to that which has developed for most other international commodities. Is this concern warranted? Considering the fact that uranium is highly dispersed about the world, one would expect the development, ultimately, of a diverse set of suppliers. There is no geological reason to expect that uranium is concentrated in so few countries as the table shows. More likely, the areas with large known reserves have been more carefully explored, for they tend to lie within the developed nations. Uranium has thus far been found in over 30 countries, and even now it is generally accepted that only 15 per cent of the earth's land surface has been well explored for uranium. The degree of concentration of supply shown in the table should decrease as existing small producers expand and new countries enter.

If these developments are likely, then there is no reason in principle why an international market for uranium should not "work," in the sense that suppliers and customers could trade with one another through a combination of spot transactions and long-term contracts. Were this to happen, then the issue of future access to supplies in the market would not arise; the only question would concern future prices, and these could reasonably be expected to be set by competitive forces. After all, most nations are dependent to some degree on international supplies of critical raw materials such as oil, natural gas, and other inputs for industrial processes. Nations build large installations which rely on imports, yet make no attempt to tie down supplies for the economic life of the capital facilities. The normal concern is to negotiate firm contracts for reasonable lengths of time; the contract period rarely extends very far beyond the time required to bring on new sources of the particular commodity (say, a decade), and often is much shorter. If the market works well, there need be no concern with the lack of "coverage" of the long-term resource needs for a particular industry or facility. A combination of spot sales and contracts for supplies 5 to 15 years forward should be sufficient, and there should be no need for consumer nations to try to gain privileged access to the reserves of supplier nations.

Of course, there is always a special sensitivity to dependence on foreign sources of energy materials. Energy affects all sectors of the society, and not just one installation or industry. The concern about oil dependence is universal, and the oil problem adds urgency to the uranium issue, if only because it is possible for any given nation to achieve autarky in the nuclear power cycle. Moreover, the fact that the market for uranium can perform adequately "in principle" does not imply that it will indeed do so.

The Availability of Enrichment Services. One circumstance makes nuclear fuel different from other commodities: a crucial step in its processing--namely its enrichment--is concentrated in the United States. There is only a small capacity in Europe (and it will remain small another few years), and only a portion of the USSR capacity is available to produce fuel for export. Throughout the early years of the nuclear industry, it was U.S. policy to serve all demand for enrichment services. Then, in 1974, it became evident that existing enrichment capacity was fully committed. The Atomic Energy Commission announced that it would not accept enrichment contracts for any new reactors; essentially the order books were closed until such time as a commitment was made to construct new capacity in the U.S. Unfortunately, this investment decision became tangled in a longstanding and thus far inconclusive debate over private versus public development of new enrichment facilities. As yet the decision has not been made, although the proposed fiscal 1978 budget does provide funds for a new government plant.

Apparently, this change in U.S. policy caught many consumers by surprise, and the removal of the U.S. as a "reliable" supplier sent a shock wave through the international industry. Several European countries were already involved in enrichment schemes; the U.S. action gave them greater impetus. More important, nations outside the participants in European projects sensed an insecurity of the supply of this service.

International Effects. Why should these concerns about "dependence" have become a subject of international discussion? Nations face situations of this type from time to time. A host of measures are available to deal with them--commercial policies, international treaties, spurring of domestic supplies, suppression of domestic demands, stockpiles.

Here we come to the aspects of uranium that make it "special." It can be argued that the fears of dependence are acting as a spur to the spread throughout the world of material suitable for nuclear weapons, for so long as supplies of reactor fuel appeared to be secure, there was relatively small commercial incentive for nations outside the U.S. and Europe to develop their own enrichment capacity. Soon after the U.S. policy change a number of arrangements were made (for example, a German deal with Brazil) which involve the transfer of enrichment technology into new areas of the world; these developments have become associated with the dependence issue. In addition, the concern about the supply of uranium and enrichment has been used as a justification for fuel reprocessing and the use of mixed-oxide fuel. Finally, concern that the resource base may be inadequate for a substantial light-water-reactor economy leads to a push for the breeder reactor, which in turn requires the construction of reprocessing plants and a fuel cycle based on plutonium. In short, the problem of "dependence," which was muted when the U.S. stood ready to accept new orders, now becomes more acute. The problem internationally is that dependence fears may be pushing the world into a plutonium economy at a faster rate than necessary, leading to increased problems of nuclear proliferation.

It should immediately be said that the products of the nuclear fuel cycle are not the only contributors to the proliferation problem. Research reactors and small, clandestine reprocessing plants are also possible sources of weapons material. Thus there is no simple, decisive action that will eliminate the proliferation threat; there are only partial gains to be had by limiting some of the sources of weapons material and reducing some of the incentives for weapons possession. It is beyond the scope of this article to discuss and analyze the overall risks and benefits of the plutonium economy, or of the nuclear industry as a whole. Rather, the issue addressed is whether the accessibility of weapons material is being increased by the dependence problem. After all, whatever one's view of the plutonium economy, it is reasonable to argue that its advent is a sufficiently serious step that we should avoid being pushed into it under pressure that might well be avoided. If we are to live with this system and its leavings for centuries to come, it seems worthwhile to devote serious attention to the preparation of the technologies and human institutions that will manage it. Few would argue that our current systems of international controls and safeguards are yet adequate to the task.

A second point where the dependence problem creates international spillovers is in the competition for access to uranium reserves: some forms of competition for long-term supplies may actually constrain the uranium market so that it cannot perform the function of balancing supplies and demands, now and in the future. Such actions may thus <u>contribute</u> to the very political instability which earlier was credited with causing a good deal of the dependence problem. There are growing indications that major consuming nations are attempting to gain control over the resources of particular supplier countries. This might be achieved by bilateral treaties or protocols, by special barter arrangements for other components of the fuel cycle, or by other special country-to-country concession or marketing arrangements.

Several advantages can be gained if such special rights are obtained, of course. The purchasing country may gain control over the resources, and thereby guarantee a long-term supply for its own reactors. Moreover, if the purchaser is a reactor vendor, it may be possible to use such special rights to back up package deals for "reactors with fuel" and thus gain advantages in markets for equipment. In return for these advantages to the importer, the exporting country may be offered a host of inducements--economic, technical, and diplomatic.

There are at least three problems with nation-to-nation economic and political barter in the place of the arms-length dealings characteristic of a conventional commodity market. First, there is the matter of economic efficiency. Under such arrangements, low-cost resources may sit untapped while high-cost reserves are exploited. This might happen, for example, if low-cost ores in an exporting nation are held in reserve for the very-long-term needs of an importing customer (say, by bilateral treaty) while other importer nations must exploit higher-cost resources elsewhere.

Second, if supply from an area is closely tied to the state of relations between two particular nations, then the vulnerability of supply to political events may be increased over what it would be in a market context. So far as the exporting nation is concerned, an exclusive concession may be rendered unacceptable by conflicts between exporter and buyer over unrelated issues, or by changes in internal politics. In a period when relations are disrupted, supply may be interrupted (or at least made less reliable) to third party customers.

Finally, and perhaps most important, if major consuming nations can tie up resources through bilateral deals, then the access to supply becomes less certain for the consumer who does not (or cannot) make such an arrangement. That is, when most resources are politically committed to a few customers, then the margin of material coming on the market for contract may become relatively small and intermittent. In such a situation the outsider will be less confident of his ability to secure supplies, and thus less willing to depend on the market. His natural reaction will be to seek bilateral deals of his own, or to lessen his dependence on imported uranium by moving more quickly to the breeder reactor or to fuel reprocessing.

In short, when confidence in the market mechanism fades, then the actions taken to secure supplies often tend to make the situation even worse. Even the U.S. cannot avoid this issue; though we have substantial domestic resources of uranium, we have no export restrictions on uranium, and several foreign countries are exploring for new resources in this country. If exports threaten to become significant in terms of future U.S. needs, and if the U.S. restricts exports to protect its own long-term independence (as Canada has done), then we can hardly expect others not to seek a similar level of control over <u>some</u> reserves. In the worst circumstance, the commodity market in uranium could disappear. Some nations would be more secure, no doubt, but the dependence concerns of others would be very much heightened.

Thus there are many aspects to the dependence problem, and actions taken because of concern about this issue can have significant effects on the international community. We must better understand how serious the problem is (if it is less serious than it appears, that information may itself be of help), and then search for policy measures that may lessen the difficulty.

"Dependence" in the Medium Term

By year-end 1975 nuclear generating capacity worldwide had grown to approximately 80 gigawatts-electric (GWe). In the wake of the oil crisis, nuclear power appeared even more attractive than before, and predictions of accelerated growth were common. The higher of the two forecasts in the figure on page 14 is representative of the outlook within the nuclear industry as of early 1976. The data are from an influential study by the Edison Electric Institute, Nuclear Fuels Supply (March 1976), and they are entirely consistent with figures quoted by the U.S. government as of late 1975 and early 1976.

Also shown in the figure is a set of estimates based on conditions in early 1977; the downward revision in expectations for the nuclear industry has been significant. More will be said later about these revised estimates; but first it is important to point out that the EEI demand estimates (and others like them) served as the basis for alarm about the ability of the fuel supply system to keep up, and helped foster the idea that dependence on international sources was risky. In the U.S., for example, concern was expressed about an impending shortage of enrichment capacity in 1983, and about uranium capacity as well. The table on page 15 shows the EEI projection of the planned world-wide expansion in enrichment facilities to 1985. Normally, the capacity of an enrichment plant is given in terms of units of work that can be put into the separation of U^{235} from U^{238} or "separative work units" (SWU). Existing U.S. capacity--about 16 million SWU--is to be increased by the implementation of two programs: a "Cascade Improvement Program" (CIP), which increases capacity solely through process refinements without raising power consumption; and a "Cascade Uprating Program" (CUP) which increases capacity still further, but at the expense of additional power consumption. CIP represents an increase of roughly 5.8 million SWU per year; CUP brings an additional 4.7 million; the result is a total U.S. enrichment capacity of 27.7 million SWU per year. CIP and CUP are to be completed by 1985, and the table takes no account of additions beyond that.

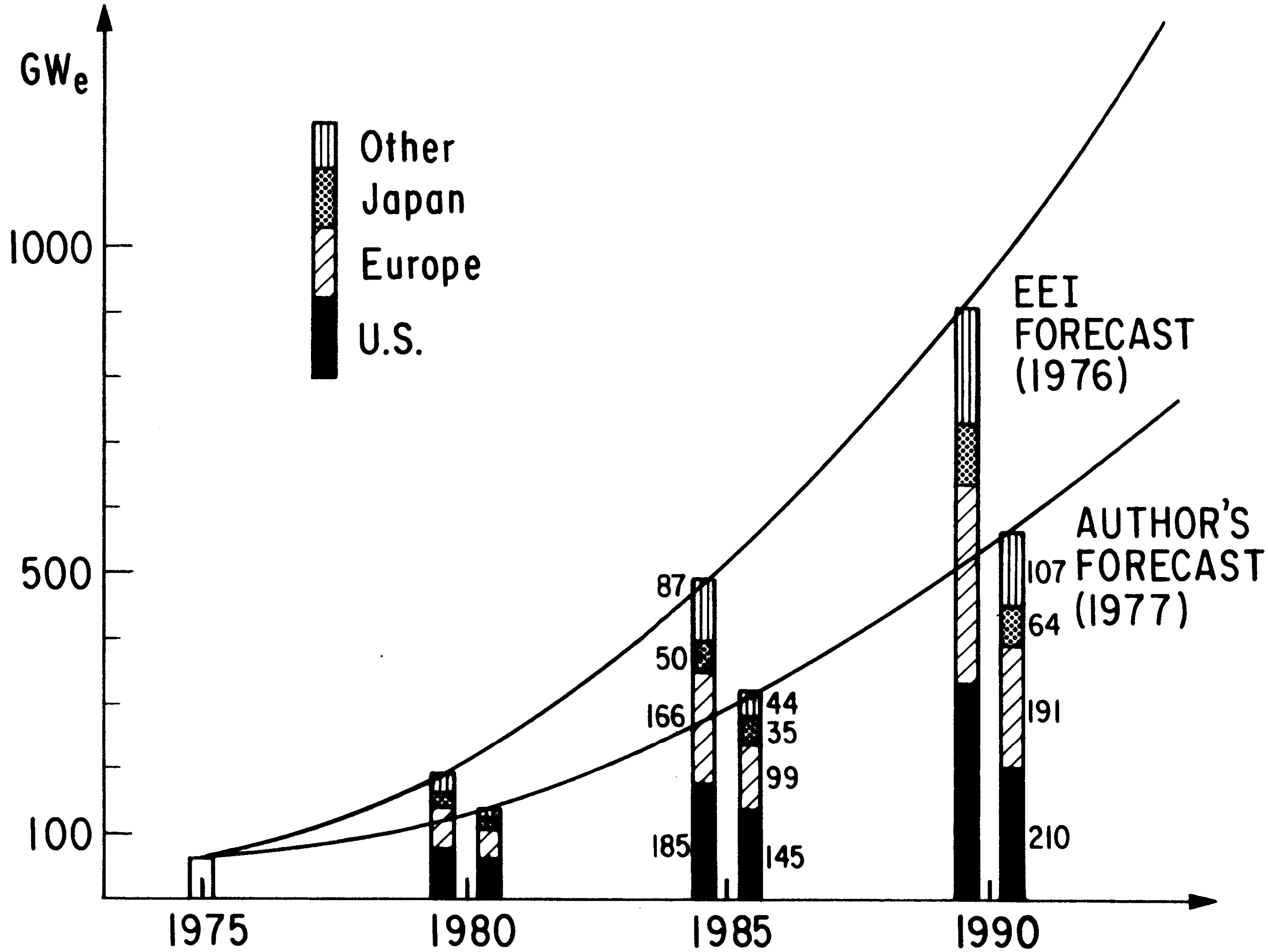

FIGURE 2. PROJECTIONS OF NUCLEAR POWER GROWTH

Table 2. Projections of Enrichment Capacity and Demand

(million SWU per year)

Year	Capacity						Total Demand
	USA	Europe			USSR	Total	
		Fr. & U.K.	Eurodif	Urenco	(Export)		
1976	16.1	.6	-	-	.8	17.5	10.9
1977	17.1	.6	-	-	1.6	19.3	12.4
1978	18.4	.6	-	.2	2.5	21.7	15.3
1979	21.6	.6	1.5	.5	3.0	27.2	21.3
1980	24.6	.6	4.5	1.0	3.0	33.7	25.7
1981	25.3	.5	7.5	1.4	3.0	37.7	29.8
1982	25.3	.3	10.2	2.0	3.0	40.8	33.6
1983	25.5	-	10.7	2.0	3.0	41.2	40.2
1984	26.7	-	10.7	2.0	3.0	42.4	48.4
1985	27.7	-	10.7	2.0	3.0	43.4	54.5

European capacity, which presently consists of two small plants in the UK and France, is assumed in the table to grow by the construction of two enrichment ventures. Urenco-Centec, a joint venture of the German, Dutch, and British governments, will employ a new centrifuge technology. It is assumed to reach 1 million SWU per year by 1980, and 2 million by 1982. Eurodif, an organization sponsored chiefly by France with the participation of Belgium, Italy, Spain and Iran will use the traditional method: gaseous diffusion. Its capacity is assumed to reach 1 million SWU per year by 1979 and grow to a full output of 10.7 million SWU per year by the mid-1980s. The total capacity of the Soviet Union and other communist countries is not known with accuracy, but it is estimated that approximately 3 million SWU per year is going to be committed to the export market. In addition to these firm enrichment plans there are a number of proposals around the world. A list of these, drawn from the EEI study and reports in Nucleonics Week and Nuclear News, is shown in the table on page 17.

The EEI reactor projection presented on page 14 translates into demand for enrichment as shown in the rightmost column of the table on page 15. (Note that communist countries are excluded.) This earlier forecast showed demand for enrichment services outstripping the expected capacity by sometime in 1983. This estimate is consistent with recent market forecasts by Eurodif which assess a total non-communist enrichment demand of 56.4 million SWU by 1985, and of 78.8 million SWU by 1988 (reported in Nuclear Fuel, October 11, 1976).

U.S. Actions. These projections of shortage in enrichment capacity are mirrored in ERDA's contract-making. ERDA has three types of contracts with both domestic and foreign customers:

Table 3. Prospective Additions to SWU Supply

Enterprise	Technology	Participants	Expected Size (million SWU per year)	Date
Planned:				
ERDA[(a)]	Diffusion	USA	8.75	Mid 1980's
Urenco[(b)]	Centrifuge	UK/Holland/FRG	8	Late 1980's
PNC	Centrifuge	Japan	5	?
STEAG	Nozzle	FRG	?	?
UCOR	Nozzle	South Africa	5	Mid 1980's
Potential:				
Australia	Centrifuge	Australia/Japan	?	?
Canadif	Diffusion	Canada/France	?	?
Brinco	Diffusion/Centrifuge	Canada	8	1983
Brazil	Nozzle	Brazil/FRG	1 to 2	?
Saskatchewan	Centrifuge	Canada	?	?
Coredif	Diffusion	Western Europe	9	1986
Centar	Centrifuge	USA	1 to 3	?
Garret	Centrifuge	USA	1 to 3	?
Exxon	Centrifuge	USA	1 to 3	?
UEA	Diffusion	USA	9	?

Notes:

(a) Expansion of existing ERDA facility at Portsmouth, Ohio.

(b) This is in addition to a first stage of 2 million SWU, the expansion to depend on marketing success.

- Requirements contracts, whereby ERDA agrees to supply all the enrichment services of a specific reactor, whenever it comes on line, up to a cumulative separative work ceiling over the life of the contract (usually 30 years). This type of open-ended contract was offered only up to 1973.

- Long-term, fixed commitment contracts, whereby the customer agrees to take (and ERDA agrees to supply) fixed quantities of separative work over a ten-year contract period, and to provide a rolling ten-year advance notice for additional requirements.

- Conditional contracts, which ERDA was to convert to regular long-term, fixed commitment contracts if the use of plutonium as fuel in light-water reactors were approved by the Nuclear Regulatory Commission.

In early 1974, the requirements and fixed commitment contracts held by ERDA, plus the expressions of interest by other parties, yielded a total far exceeding the capacity of the enrichment plants the U.S. had taken a firm decision to build. This circumstance led, in July 1974, to a "closing of the books" for further orders from ERDA. Some customers were given only the newly instituted "conditional" contracts, which could be honored if enrichment capacity were freed up by the adoption of recycling. In effect, the only way a new customer could gain access to ERDA enrichment services was (and is) by purchasing an existing contract or some portion of it--a process known as "assignment."

This situation developed against the background described earlier. It had been U.S. government policy to provide an unlimited supply of enrichment services to the non-communist world; and indeed, on August 7, 1974, President Nixon guaranteed foreign countries that the U.S. would, under any circumstances, fulfill the fuel requirements under the conditional contracts. Nevertheless, the closing of ERDA's order books caused many foreign governments and utilities to discount the dependability of U.S. supply. This re-evaluation provided the incentive to search for alternative arrangements that would offset the dependence on the U.S. Accordingly, U.S. officials concluded that new enrichment capacity must be commissioned as quickly as possible if the U.S. was to maintain its world leadership in enrichment services and nonproliferation initiatives. In June, 1975, the Ford Administration proposed that this next increment of enrichment be developed by private corporations rather than by the U.S. government, but the enabling legislation for the private sector scheme failed to pass the Congress. As of today, plans have been set in motion to build an 8.75 million SWU extension to ERDA's Portsmouth plant (see page 17), and President Carter's energy program renews this commitment. Beyond this one plant expansion, however, the U.S. policy with regard to enrichment remains to be sorted out by the new administration and the Congress.

The concerns of recent years also extended to the adequacy of uranium supply for the growing industry. The EEI forecast of U_3O_8 demand implies a doubling of current mining and milling capacity by 1979--a task that the EEI study judged to be attainable (see the table on page 5). But the forecast requires another doubling by 1983 and yet another doubling within five to six years after that! The problems of such a rapid capacity expansion in the mining and milling industry--exacerbated by political uncertainties--have created the fear that uranium feed will be lacking.

Lower Forecasts. The paragraphs above describe the outlook in late 1975 and early 1976. Since then, circumstances have changed significantly. The predictions of reactor growth, it now turns out, were overstated, due to a number of factors. The national prestige associated with "going nuclear" lead to wishful forecasts and made nations reluctant to revise estimates downward. Increased licensing and environmental delays and rising nuclear-plant costs have also been significant. Most important, however, the recent recession and energy price increases have dampened the growth of electric power demand.

In order to form a more accurate picture of the next ten to fifteen years, I have prepared an updated set of reactor forecasts. They are shown in the figure on page 14 alongside the EEI predictions. The U.S. forecast takes account of recent ERDA projections and work at M.I.T. by Joskow and Rozanski. The figures very likely are still too high; reactor start-up dates are still slipping. The estimates for Europe and Japan are based on a recent assessment by the OECD, which is reported in its World Energy Outlook (1977). Advantage also was taken of forecasts by the International Atomic Energy Agency and surveys of reactor progress published by Nuclear Engineering International. Very likely the figures are biased upwards, at least to 1985, for reactor dates are slipping abroad as well.

The 1975-Fuel-trac "Worldwide MW Survey," published by the Nuclear Assurance Corporation was used as a basis for projecting the "other" countries. Since the Fuel-trac forecast was very optimistic, slippage was assumed to occur. Specifically, reactors assumed to be on line by 1977 were presumed to be one year late, reactors due in 1979 were assumed to be two years late, and so forth, to the point where all reactors scheduled for 1983 and after are a total of four years late.

Though I believe that, overall, even the lower forecast of the figure on page 14 is still optimistic, the precise numbers are not crucial to the discussion. What is important is the general magnitude of the downward shift even from very recent assessments of the nuclear picture. Rough estimates of that shift have significant implications for uranium dependence, for conditions have been created that would allow the buildup of large stockpiles of LWR fuel, and the way this opportunity is handled has important implications both for new enrichment ventures and for the stability of the uranium industry.

Tails Assays. In order to talk about the quantities of fuel that may be involved, it is necessary to introduce a few technical details about the operation of enrichment facilities. As the enriched material is produced, there results a waste stream with some residual U^{235} left within it. This waste product is called the enrichment "tails." The amount of U^{235} in the tails can be controlled. Additional cycles through the separation process will produce 3-per-cent enriched product in greater quantity, and the assay of U^{235} in the tails will be reduced. But more and more work (SWUs) per unit of product is required as this process proceeds. Thus, for any particular amount of reactor fuel (3-per-cent enriched product) there is a tradeoff between the quantity of uranium feed (U_3O_8) and the quantity of enrichment services (SWUs) required.

Today, the ERDA enrichment plants are running at a 0.25 per cent tails assay (that is, the waste stream contains 0.25 per cent U^{235}). If the tails assay were dropped to 0.20 per cent, then for the same quantity of 3-per-cent enriched fuel the U_3O_8 feed requirement would go down by 10 per cent. On the other hand for the same quantity of output, the SWU input would go up by 16 per cent. Now, for any given price for enrichment (dollars per SWU) and price for raw material (dollars per kilogram of U_3O_8) there is some tails assay that produces fuel at the lowest cost. At current prices, the optimal tails assay is below the current operating rate: probably somewhere around 0.20 per cent tails rather than the current 0.25 per cent. However, the ERDA operation is influenced by the fact that ERDA is in the process of working down a large government-owned stockpile of U_3O_8.

As noted in the figure on page 3, enrichment tails are not thrown away. Tails containing, say, 0.25 per cent U^{235} can be stored and, at a later date re-introduced into the enrichment process and processed further, perhaps to the 0.20 per cent level or below. In fact, ERDA holds considerable stocks of uranium in the form of enrichment tails at 0.25 per cent and above.

Fuel Supply in the 1980s. By making some assumptions about tails assays in the future, it is possible to construct a picture of what the lower reactor forecast on page 14 means for the enrichment industry. This may be done by calculating, area by area, the demand for fuel over time as compared to the fuel that could be produced in that year. (It is assumed that the enrichment plants listed on page 18 are actually built on the schedule shown.) What results is a number signifying the potential stocks of LWR fuel. The calculation is made as follows:

- SWU requirements are calculated for the estimate of reactor buildup shown in the figure on page 14. ERDA is assumed to continue to operate at a 0.25 per cent tails assay, as at present. New European capacity is presumed to operate at 0.20 per cent from the beginning. Little is known about the USSR exports, but they are evaluated as if produced at a 0.25 per cent tails assay.

- An estimate is made of shipments of LWR fuel from ERDA plants based on fixed-commitment contracts and the realization of requirements contracts as estimated by ERDA as of November 30, 1976. These shipments are subtracted from the gross demands of U.S. utilities, Europe, Japan, and "other" nations.

- Based on ERDA estimates, it is assumed that 16.1 million SWU are devoted to preparing material for domestic military and research programs through 1988.

- ERDA enrichment plants are assumed to run at full capacity, and any deficit in relation to contracted shipments becomes a demand on the ERDA stockpile. Excess production augments the ERDA stockpile.

- All Urenco and Eurodif production is credited to Europe, as are all exports from the USSR.
- A reactor capacity factor of 0.70 is assumed throughout; that is, after an early shakedown period all reactors are assumed to operate, on average, at 70 per cent of their rated electrical capacity.

Such a calculation predicts that U.S. utilities have ordered more fuel than they will use over the next decade or more. ERDA continues to add to stocks of enriched material well into the 1980s. Europe also is predicted to have excess supply--all the way to 1988. The rest of the non-communist world is in a similar situation as late as 1984. The crossover date when current demand exceeds capacity advances to 1987 from the 1983 crossover shown in the table on page 15.

In short, if these enrichment plants are operated, stocks of LWR fuel will build up around the world. The figure on page 24 shows the buildup that could occur under the assumptions made here. Two different measures of stockpile size are shown. One is the total number of SWUs that have gone into the material in the stocks. (Stocks as of January 1, 1977 are credited as if they had been produced at a tails assay of 0.25 per cent). The other is the number of years of operation of 1 GWe reactors that could be run, at a capacity factor of 0.70, with the fuel in the stock. Since the fuel enrichment actually varies slightly above and below 3 per cent depending upon the reactor type, it is assumed in preparing the prediction that the LWR mix is two-thirds pressurized water reactors and one-third boiling water reactors--roughly the shares today. (At a tails assay of 0.25 per cent each 100,000 SWU will provide 1 GWe-year of LWR fuel, two-thirds of which is to be used in PWRs and one-third of which is to be used in BWRs.)

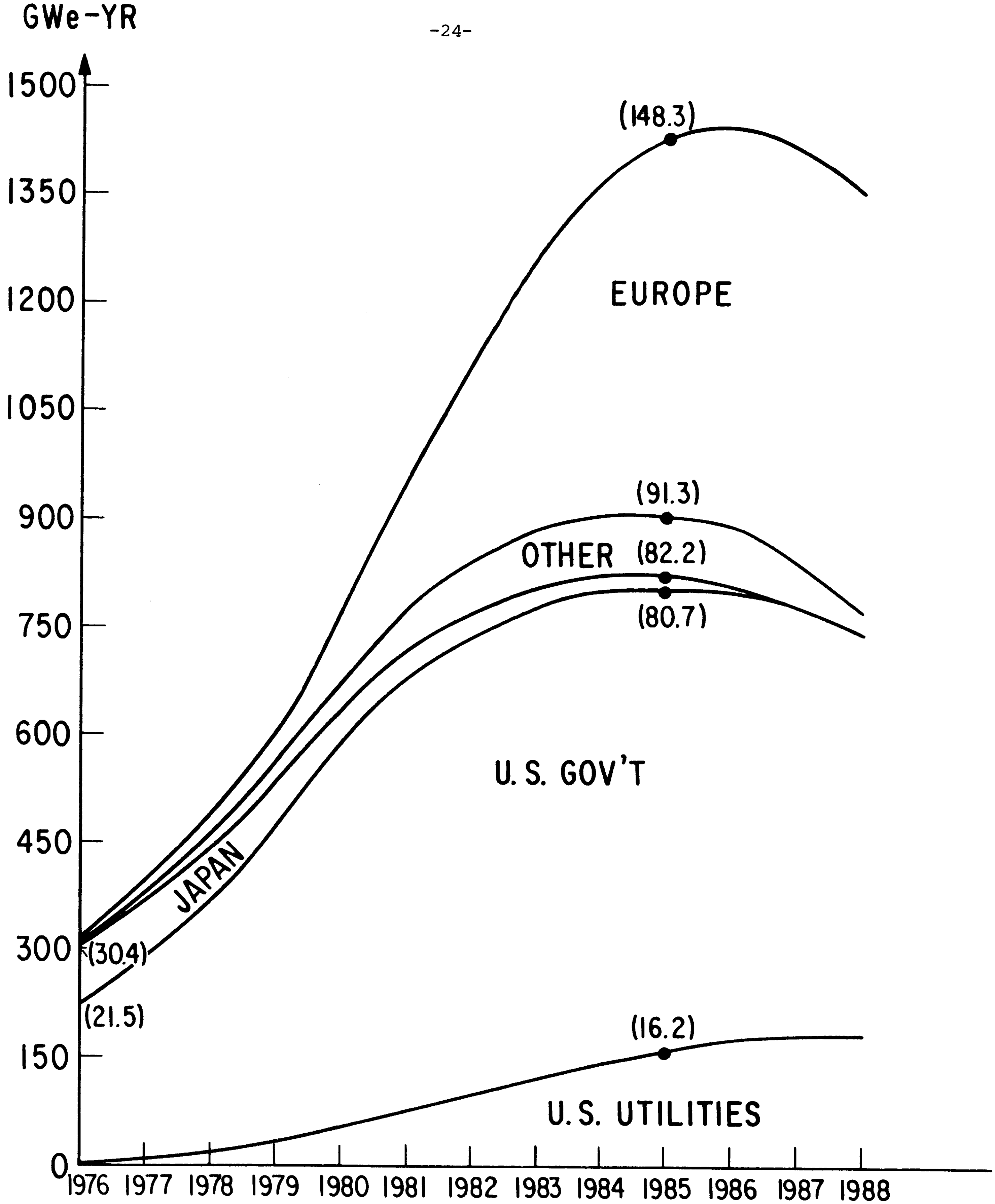

FIGURE 3. ATTAINABLE STOCKS OF LWR FUEL IN GWe-YR, AND IN TERMS OF ENRICHMENT INPUTS IN MILLION SWU (SHOWN IN PARENTHESES)

As the figure indicates, ERDA already held a stockpile of 21.5 million SWU at the end of 1976. The Japanese have a stockpile of approximately 8.9 million SWU, created by an advance sale by the U.S. to Japan in 1973, and held in the U.S. It is due to be depleted on a fixed schedule to meet a portion of contracted requirements. Here it is assumed to be drawn down at a uniform rate over ten years. Current stocks elsewhere are not known and are assumed to be zero.

The potential stock buildup is striking. The countries in the "other" category build up stocks slowly over time. By the mid-1980s they hold stocks equal to roughly two years of demand at that time. The Japanese hold ERDA contracts that follow our forecast of their reactor growth very closely, though this is masked in the stock figures by the influence of material from the advance sale. In Europe, large stocks are attainable under the assumptions made here. The stocks in the mid-1980s could build to over four years worth of total demand for reactor fuel.

The stock buildup in U.S. utilities is modest--never more than a year's consumption. The stocks held by ERDA, on the other hand, become very large--rising as high as 650 GWe-years in the mid-1980s.

Complicating Factors. Of course, the projection shown on page 24 is only a forecast of what is "attainable;" there are several reasons why it may not come about. After all, several assumptions lie behind the calculation, and most of these concern decisions that have yet to be made. First, it is unlikely that the demand for Soviet enrichment will reach the 3 million SWU per year assumed to be available for export. Second, either unavoidably or by conscious decision the Urenco or Eurodif plants could be delayed. Either of these events would lower the stocks credited to Europe. On the other hand, several of the prospective plants listed on page 17 are well on the way to construction. Some combination of these plants might yield a considerable increase in total capacity outside the U.S.

Several things could influence the ERDA stocks as well. ERDA could decide to recycle tails rather than process raw U_3O_8. Under some operating schemes this could involve a reduction of as much as 8 million SWU or roughly 80 GWe reactor years. Or, ERDA could lower the tails assay of the enrichment system as a whole, say to 0.20 percent, which also could cut the stockpile size. On the other hand, if built on the current schedule (2.1 million SWU in 1984, growing to 8.75 million SWU in 1986) a plant the size of the planned Portsmouth expansion would add another 350 GWe reactor years of fuel to U.S. stocks by 1988.

On another point, there are several factors that could shift the total U.S. domestic stockpile between ERDA and the utilities. It is assumed here that ERDA deliveries follow the anticipated schedule of requirements contracts. If the slippage in reactor construction involves many power plants holding requirements contracts, the deliveries will be reduced and stocks will grow at ERDA instead of in the consumer's hands. It also is assumed that deliveries follow the specified schedule of reactors under fixed-commitment contracts, assuming a capacity factor of 0.70. In fact, many fixed commitment contracts involve an implied capacity factor above 0.70; some are as high as 0.75 or 0.80. These high capacity factors are unlikely to be attained; even the 0.70 used here seems optimistic considering recent reactor operating history. However, if fuel deliveries are actually made on the contracted schedule, then a portion of the stocks now credited to ERDA actually will build up in the hands of the utilities. ERDA could call another "open season" whereby adjustments are allowed in the fixed-commitment contracts, and this would have the effect of shifting the stock-holding burden back onto ERDA. Of course, the degree to which this happens depends on how badly the U.S. utilities, or foreign buyers, want to get out from under the burden of holding the stocks themselves.

Then there is the question of U.S. government policy about building and holding stockpiles. The ERDA stockpile will be expensive to create, and the funds must be provided from the federal budget. It is quite possible that ERDA facilities would be run at less than full capacity (this has happened in the past) or that programs to increase the electrical power inputs to the enrichment plants would be postponed. Or, if many enrichment contracts were cancelled or postponed, ERDA might run into limitations on uranium feed, which is delivered to ERDA by the customer a few months before the enrichment is to be done. ERDA would then face a choice of purchasing feed directly or changing the amount of feed that enrichment customers are required to provide.

Even with all these complexities, the basic situation is clear. The world now has the opportunity to create sizable stockpiles of LWR fuel. Whether in fact we shall do this depends on decisions by the U.S. government, the countries of Urenco and Eurodif, and the major consumer countries and their utilities. The problem is not inadequacy of supply, but whether or not to purposefully create surplus over the next decade.

The choice will have tremendous consequences for the domestic uranium mining and milling industry. A present, ERDA is managing the enrichment plants under a "split tails" policy. Though the diffusion plants are operating at a tails assay of 0.25 per cent, ERDA is transacting with customers at a tails assay of 0.20 per cent (which implies less uranium feed) and making up the balance of the U_3O_8 demand from the government's U_3O_8 stockpile. This split tails strategy serves as a means of converting these government stocks to a more highly processed form. It is presumed that this policy will continue until at least 1982, when the U_3O_8 stocks will have been depleted.

Given this presumption and the operating conditions specified on pages 22-23, the effect of the stockpiling decision on the domestic U_3O_8 industry can be approximated. If ERDA were to decide to satisfy only demand for reactor fuel as it occurs, with no provision for building a stockpile, the demand on uranium mines and mills in 1982 would be 22,500 metric tons of U_3O_8; ERDA would have to supply an additional 1,900 metric tons from the government stockpile. On the other hand, if ERDA were to use to excess SWU capacity (above that needed to satisfy current domestic demands and foreign contracts) to build a stockpile of LWR fuel, the demand on the mining and milling sector in 1982 would be 30,500 metric tons of U_3O_8; ERDA would have to supply an additional 2,600 metric tons of U_3O_8 from the government stockpile.

It is evident that considerable uncertainty is created by the peculiar linkage of the uranium-mining industry to an enrichment and stockpiling policy that can (and probably will) change over time. To quote a representative of the French atomic energy agency, "...it is now more important for the uranium mining industry to know what the long-term stockpiling policy of utilities or governments will be than to know if it is the low or the high estimate of installed reactor capacity which will actually be achieved in a given year."

Pros and Cons of Stockpiles

Given the stockpiles plotted on page 24 as one scenario, it is interesting to contemplate the implications of continuing on the path now being followed--that is, the path of building and operating the enrichment capacity shown in the table on page 15.

Calculations of Cost. The first question concerns the cost of building the stockpile. A very crude calculation can show at least the order of magnitude of the numbers. The evaluation can be based on the following set of simplifying assumptions.

- The stockpile is taken to comprise 3% enriched uranium, and there is no stockpile of unenriched U_3O_8.

- The cost of the stockpile is to be compared with a "no stockpile" option whereby the total stock held within and outside the U.S. is assumed to remain at its 1976 level.

- The cost of material for the stockpile is to include the average cost of uranium and enrichment services. Enrichment is assumed to cost $75 per SWU, and the associated uranium feed (roughly 1.56 kilograms per SWU at 0.25 per cent tails) is assumed to cost $100 per kilogram. The cost of adding one GWe-yr of fuel to the stockpile is $23.1 million. This cost (in 1976 dollars) is assumed constant over the period of the calculation.

This set of assumptions allows the calculation of the cost per year through 1986, when it hits its peak. As of that year, the stockpile has some terminal value: it will continue to serve some security function, or it could be drawn down in the longer-term future, displacing other costs. In this simple calculation no attempt is made to estimate this value.

Now the results: the cost of building the worldwide stockpile starts out at about $1.9 billion per year in 1977 and grows to approximately $4.3 billion in 1981. It then falls to zero by 1986. At 8% interest, the present value in 1977 of the cost of building the stockpile to 1986 is around $20 billion.

Another approach is to calculate the carrying charges on a strategic stock. For example, under our assumptions a 1 GWe reactor needs fuel costing \$23.1 million each year. At 8 per cent interest, the carrying charge on a 1-year stock is \$1.8 million, or 0.3 mills per KWH for each year's worth of stock held in reserve. These figures may be compared with a rough estimate of the total fuel cycle cost (of 3 to 5 mills/KwH) or of the total cost of power at busbar (20 to 28 mills/KwH).

These are very rough numbers. In a more careful estimate account should be taken of the fact that the ERDA U_3O_8 stock already exists and has a low marginal cost, and one would need to worry more about the likely patterns of change in the uranium price as depletion occurs. But whatever the precise numbers, the costs of a stockpile are seen to be large in absolute terms, but relatively small in relation to the total costs of nuclear power. The issue to be raised is whether the gains are worth the burden.

Benefits of a Stockpile. One way to look at the benefits of the stockpile is to construct some indicator of the level of "independence" that it might provide on a worldwide basis. For example, one may calculate how many years of growing demand the stockpile can cover in the event new enrichment capacity is delayed. If no enrichment facilities were built beyond those listed in page 15, the stockpile would not be drawn down to the 1976 level until 1992. If the Urenco and Eurodif plants were each delayed by two years, and no additional capacity were built elsewhere, the stocks built in the 1970s and early 1980s would still allow world demand to be covered through 1990. One can also look at the quantity of fuel available to serve the needs of areas that have no indigenous enrichment capacity. Under the scenario shown on page 24, the worldwide stocks in 1985 are over 25 times the fuel demand by "other" countries in that year, and over 15 times the combined demand of "other" countries plus Japan.

Clearly, if stocks of anywhere near this size were available, there should be less pressure in a number of countries to close the fuel cycle within their own borders. With a cushion of LWR fuel available, either in domestic stocks or in some secure external stockpile, the security advantages that are claimed for domestic enrichment capacity or fuel reprocessing are much reduced.

Moreover, the choice of stockpile policy has an effect on net demand for uranium, and this may have important effects on its supply and price. If there is a cut-back in the anticipated need for new mines, then exploration will likely be retarded and the world will learn less about the extent of uranium resources. A decision to build enrichment facilities on schedule and to accumulate stockpile will maintain the growth of the mining and milling industry. On the other hand, a related effect might be higher prices if uranium demand in combination with stockpiling puts too much pressure on mining and milling capacity.

Stockpile Management. A stock of uranium hanging over the market will serve to create uncertainty about future demand and price. The worry is that the stock might enter the market at any time, suppressing uranium prices, and the risks of investment in mining and milling are raised as a result. Thus the form of ownership and management of the stock is crucial. It could be dispersed in the hands of many utilities and/or nations; if they forbid any of the enriched uranium from leaving the country once it has entered, the stockpile would increase security without threat of disruption of markets. If holders of the stock allow trading, on the other hand, there would be a constant threat that stockpiles might come on the market. In such a case the price uncertainty could be great, and this could have significant effects on the expansion of uranium supply and enrichment capacity.

If the stockpile were held by a single nation--as would be the case, for example, if importers took only the uranium needed on a current basis and the United States built the stockpile alone--the nation holding the stockpile would be in a position of significant power over the market. There might be commercial advantages to holding such a stockpile. The holder also might gain bargaining and negotiation advantages on international issues such as proliferation. In an article in Foreign Affairs (July 1976) Senator Ribicoff has suggested that the U.S. follow such a policy, and seek to use our current enrichment monopoly to gain leverage on proliferation issues.

As another alternative, the stockpile could be held under international auspices. This also is a situation which could yield a wide variety of results: An international body could use the manipulation of a stockpile to establish commodity prices over considerable periods of time. (In fact, managers could hardly avoid having some effect on price, even if their charter forbade them to exert such leverage.) It could use the stockpile to help form a uranium cartel, or to prevent one. It could protect the interests of small, "dependent" nations through special access arrangements; this could ameliorate the fears of dependence cited at the outset. Further, it could provide fuel from internationally-held stocks to substitute for resources foregone when a nation does not pursue fuel reprocessing.

Thus there are myriad possibilities for management. The costs are great, but so may be the benefits. The issue is far from settled. It will be greatly influenced by decisions in the coming year about ERDA enrichment procedures, and by plans for Urenco, Eurodif, and purchases from the Soviet Union.

Implications For Longer-Term Adequacy

The recent revision in expectations about reactor growth also has a significant effect on perceptions of the long-run adequacy of uranium resources. The table on page 34 presents a rough calculation of the uranium requirements for the LWR industry to the year 2000. The reactor forecast developed earlier in this article is used through 1990. After 1990, nuclear capacity is assumed to grow at 8 per cent per year. The reactor capacity factor is 0.70 as before. A tails assay of 0.20 is used throughout, as it is likely that all uranium will be processed at least to this extent before the end of the century, even if only gaseous diffusion plants are in use. The uranium requirements are stated in terms of (1) the cumulative consumption of resources up to any year, and (2) the total commitment of resources if, when a reactor is built, reserves are set aside to meet requirements over its full 30-year life.

The table shows cumulative demand rising to 368 thousand metric tons of U_3O_8 by 1985, and 2,414 thousand metric tons in the year 2000. By 2000, cumulative commitments will have reached 6,708 thousand metric tons under these assumptions. These requirements may be reduced by new fuel processing technologies. A laser-enrichment technology, if it can be made to work, would allow processing to 0 per cent tails. On the assumption all previous tails at 0.20 per cent are further processed by laser devices, the cumulative demand by the end of the century totals only 1762 thousand metric tons, and the cumulative commitments rises to 4897 thousand metric tons, a drop of approximately 27 per cent. If reprocessing and mixed-oxide fuel were introduced, these requirements would drop by an additional 15 to 20 per cent.

Table 4. Long-Term Uranium Requirements

	1976	1980	1985	1990	1995	2000
Installed Capacity (GWe)						
U.S.	43	66	145	210	308	453
Other	35	100	178	362	531	782
	78	166	323	572	389	1,235
Uranium Requirements (10^3 MT U_3O_8)						
No recycle, 0.20% tails						
cumulative	28	128	368	794	1,459	2,414
cumulative commitments	463	947	1,827	3,142	4,582	6,708

The question, of course, is what to compare these numbers with. The table on page 5 shows a world total of 4340 thousand metric tons of U_3O_8, taking account of reasonably assured and estimated additional resources at $30 per pound of U_3O_8. Even considering the fact that some probability distribution must be attached to these estimates, there is reason to consider this as a conservative estimate of the resources available:

- The addition of possible and speculative reserves for the U.S. as estimated by ERDA would add another 1600 thousand metric tons, for a world total of roughly 6000 thousand.

- The U.S. and Canada have been extensively explored. Many other areas of the world have not. In these two countries, the "estimated additional" resources are two to three times the "reasonably assured." If a similar pattern were to hold for the rest of the world (as it should with more exploration) the total would rise to 7000 to 8000 thousand tons.

- These figures are for a cutoff level of $30 per pound forward cost. Little is known about potentials at 2 to 3 times this cost level, yet these higher costs could be sustained by an LWR economy.

Naturally, no one knows what the true resource figures are, though our knowledge is growing rapidly. And it is well to remember that the availability of resources of uranium is not synonymous with its supply, for supply implies both the decision to exploit the resources and the development of the mines, mills, and supporting industries to do it. Still, even these rough estimates allow some interesting observations. Under the assumptions in the table on page 34, it is not until 1995 that cumulative <u>commitments</u> reach what is likely a very conservative estimate of resources. Cumulative <u>consumption</u> would not reach this level until the next century. If laser enrichment proves feasible, and if reprocessing ultimately is adopted, then these resources seem adequate to reach well into the next century.

In short, even under pessimistic assumptions, it should be 20 years before the resource constraint really begins to bind, and there is a good chance the world will not face this difficulty until after the year 2000. As a result, there is a breathing space -- albeit a short one considering the time lags in developing a major new high-technology industry -- before breeders or fuel reprocessing are required to sustain a growing nuclear contribution to energy supply. The U.S. government has decided to take advantage of this opportunity, and has postponed the commercialization of the breeder reactor and the operation of associated reprocessing facilities. Prudence requires that we use this time well, and mount an urgent effort to find a socially preferable alternative to the plutonium cycle. We also must give high priority to efforts to better understand worldwide uranium resources and supply, so that better estimates can be made of what real stringencies may be ahead.

All nuclear nations face the same world resource situation, of course, but it is much easier for the U.S. to delay the race to the breeder than it is for other major nuclear nations. We are sitting on the world's largest proved reserves of uranium; Europe and Japan must depend on the world market. Thus the hope that other nations may take a delaying action similar to ours depends critically on the present and expected future security of the supply of conventional LWR fuel. Measures to lower the fear of uranium "dependence" -- including the careful use of fuel stockpiles -- must become a critical component of U.S. policy if the desired benefits of our non-proliferation initiatives are to be realized.