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Fission Power: An Evolutionary Strategy

Harold A. Feiveson, Frank von Hippel, Robert H. Williams

The spread of civilian nuclear power technology is being accompanied by the spread of the knowledge and material required for the production of nuclear weapons. Concern has focused especially on the plutonium fuel cycle—in the short term on efforts to commercialize nuclear fuel reprocessing for the recovery of plutonium and in the long term on the related efforts to commercialize the plutonium breeder reactor.

In response to these concerns the Carter Administration in 1977 called for a deferral of U.S. programs aimed at the commercialization of the plutonium fuel cycle, and initiated national and international studies of alternative nuclear power systems that might be more nuclear weapons "proliferation resistant" (*1*). Our purpose here is to explore the potential role of such alternative systems in the development of nuclear power in the United States and abroad.

Summary. Motivated by concerns about the difficulty of safeguarding the large flows of plutonium in a breeder reactor fuel cycle, we explore the resource and economic implications of a strategy in which there is no nuclear weapons–usable material in fresh reactor fuel. The strategy involves the deployment of already developed types of advanced converter reactors which, unlike the breeder, can be operated effectively on proliferation-resistant once-through fuel cycles. Advanced converter reactors could be much more uranium-efficient on once-through fuel cycles than current systems and therefore could compete economically with breeders up to very high uranium prices. If necessary, the uranium requirements of an advanced converter reactor system could be reduced much further with the recycling of isotopically denatured uranium, but any commitment to a closed fuel cycle would be unnecessary for many decades.

We do not pretend that the problem of nuclear proliferation can be solved simply by developing an alternative to the plutonium breeder. A large number of nations could develop a nuclear weapons capability outside their nuclear power programs (*2*). One cannot, therefore, expect a nonproliferation strategy to succeed if it does not grapple with the political and security incentives and disincentives for countries to acquire nuclear weapons. More fundamentally, it is unlikely that in the long term, proliferation of nuclear weapons can be stopped while the nuclear weapons states continue to act as if nuclear weapons are politically useful things to have.

Nevertheless, we believe that proliferation resistance should be an important criterion guiding the choice of future nuclear power technologies, because some of these technologies, by providing nations access to weapons-usable material, can directly contribute to a process of "latent proliferation," whereby nations move inexorably closer to a weapons capability without having to declare or decide in advance their actual intentions (*3*). Reprocessing for recycling of plutonium is one of these technologies, since it involves the recovery of a nuclear weapons-usable material from "spent" reactor fuel and its subsequent processing and redistribution in chemically separable form in fresh fuel (see Fig. 1).

We have discussed the relative proliferation resistance of different fuel cycles elsewhere (*4*-*6*). Here we present an analysis of the technical and economic viability of some of the systems that we have proposed as alternatives to the plutonium breeder. In particular, we explore the question of whether the proposed alternatives to the plutonium-fueled breeder reactor would allow the development of fission power on a large scale.

Our current nuclear power system does not assure the long-term future of nuclear energy. It is extremely wasteful of our limited resources of uranium in high-grade ore because it exploits only about one-half of 1 percent of the fission

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energy stored in natural uranium—primarily that in the rare, naturally fissile (chain-reacting) isotope ^{235}U. The plutonium breeder reactor would alleviate this problem by transmuting the abundant "fertile" isotope ^{238}U by way of neutron capture into fissile isotopes of plutonium (*7*).

The plutonium breeder, however, is hardly a unique solution to any uranium supply problem which is likely to materialize over the next 50 to 100 years. It is unlikely to be the most economical. And it appears to be unnecessarily vulnerable to technological and institutional failures.

An alternative to the breeder is an evolutionary strategy based on already developed or commercialized advanced converter reactors (ACR's): the heavy-water reactor (HWR), the high-temperature, gas-cooled reactor (HTGR), or an advanced light-water reactor (LWR) (*8*). Each of these reactor types could be operated as a part of a fission energy system which is much more uranium-efficient than the current once-through, low-enriched uranium-fueled LWR system.

The distinctive characteristic of an ACR is that, unlike the fast neutron breeder reactor, it can be operated on a uranium-efficient once-through fuel cycle. It would therefore be possible to deploy ACR's without making an irreversible commitment to the extra complexities and proliferation vulnerabilities associated with a "closed" fuel cycle—that is, one which involves reprocessing and fissile recycling.

The option of shifting to a highly uranium-efficient closed fuel cycle would always exist, however, and could be utilized if (i) very tight uranium supply constraints appeared to be developing and (ii) it became possible in the meantime to institute adequate technical and institutional arrangements to safeguard fuel recycling facilities against the diversion of weapons-usable materials.

An ACR would have the additional advantage of being able to operate with a relatively small economic penalty on a closed fuel cycle in which only isotopically denatured fissile material was recycled, that is, on a fuel cycle in which no nuclear weapons-usable material could be recovered from fresh fuel by simple chemical separations. On a closed isotopically denatured uranium-thorium fuel cycle (see Fig. 1b) an ACR would be two to five times more uranium-efficient than an LWR operating on the current once-through fuel cycle. As a result, an ACR could both operate economically on uranium that is many times more costly than that being mined today for LWR's and dramatically reduce the rate of consumption of uranium and hence the rate of uranium price increases.

For these reasons the implementation of an evolutionary strategy would push any incentive to deploy the breeder reactor to well beyond the middle of the next century. In that period it appears likely that the evolutionary strategy could be taken one step further, in that the uranium efficiency of the ACR's could be improved to the point where these reactors could become nearly as resource-conserving as breeders.

Isotopically Denatured Fuel Cycles

We have limited our evolutionary strategy to fuel cycles that can be effectively "isotopically denatured"—that is, to systems where the fissile material in fresh nuclear reactor fuel is mixed with nonfissile isotopes of the same element to the point where the fissile material is so dilute that it cannot sustain a fast (explosive) chain reaction in a small critical mass. Weapons-usable material can be recovered from such denatured fuel only by use of isotopic separation techniques, which require considerable technical resources and time (*9*). Isotopic denaturing is a major proliferation-resistant characteristic of the low-enriched uranium fuel used in today's once-through fuel cycles and represents a quality that we believe should be given up only reluctantly in considering alternative nuclear systems.

A mixture of ^{235}U and ^{238}U is considered to be denatured for nuclear weapons purposes if the content of ^{235}U is less than 20 percent (*10*). In the low-enriched uranium once-through fuel cycles shown in Table 1, the fissile ^{235}U in the fresh fuel is diluted with nonfissile ^{238}U to a concentration of less than 5 percent—well below this limit. For the once-through HTGR fuel cycle, less ^{238}U is included in the fuel—only enough to denature the ^{235}U to the 20 percent limit. Thorium is preferable to ^{238}U as a fertile material in the HTGR and has therefore been used to replace ^{238}U up to the limit allowed by the denaturing requirement (*11*).

Because of the presence of ^{238}U in fresh denatured fuel, significant amounts of plutonium are inevitably present in

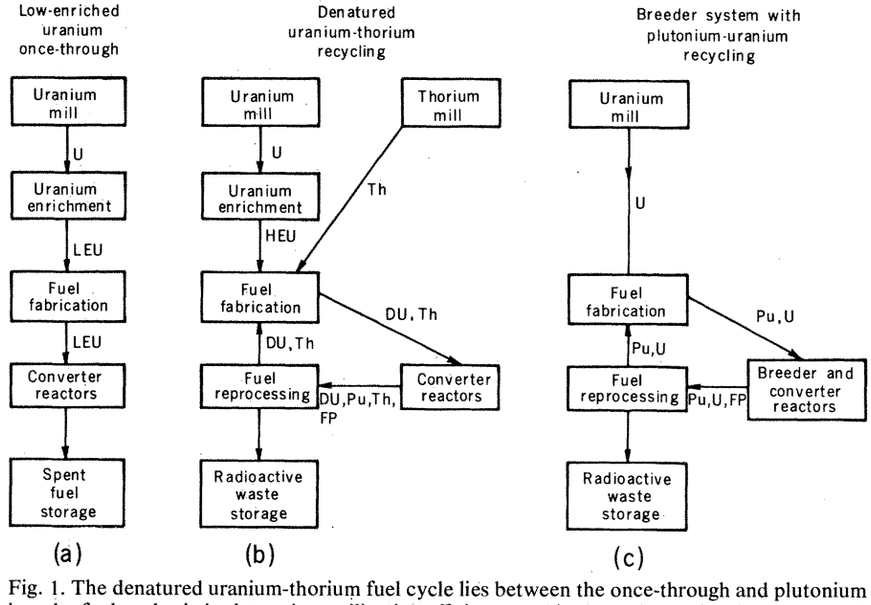

Fig. 1. The denatured uranium-thorium fuel cycle lies between the once-through and plutonium breeder fuel cycles in both uranium utilization efficiency and in the technological barriers which it offers to the diversion of weapons-usable material. In the once-through cycle (a), the uranium fuel contains low-enriched uranium (*LEU*), which cannot be used for weapons purposes without isotope separation. The spent fuel is stored or disposed of without separating from the highly radioactive fission products (*FP*) the contained plutonium (*Pu*) which has been produced by neutron absorption in the ^{238}U in the fuel. The denatured uranium-thorium recycling system (b) uses isotopically denatured uranium (*DU*) as the reactor fuel, and the spent fuel is chemically reprocessed to retrieve uranium and thorium for recycling. The enrichment of the uranium recovered from the spent fuel is restored to its initial value by the addition of highly enriched uranium (*HEU*). Since most of the fertile material in the fuel is thorium (*Th*), most of the new fissile material produced is ^{233}U, but some plutonium is still produced by neutron capture in the ^{238}U denaturant. It is assumed here that this plutonium is not recycled. The plutonium fuel cycle (c) involves the recycling of both plutonium and uranium. Both fresh and spent reactor fuel contain large quantities of chemically separable nuclear weapons-usable material. With breeder reactors eventually no externally supplied fissile material would be required—hence the absence of a uranium enrichment plant.

spent fuel. During the first few months after the fuel has been discharged from the reactor, the fuel is so intensely radioactive that recovery of the plutonium is very difficult, but the plutonium becomes increasingly accessible with remote chemical-processing techniques as the fuel cools. It is therefore critical that spent fuel from once-through fuel cycles be removed as soon as practicable after discharge from the many individual power plant sites around the world to storage at a relatively few centralized depots maintained under tight international control.

In Table 1 we show that the quantities of fissile plutonium discharged annually by the low-enriched uranium once-through fuel cycles are much less than those discharged by the liquid metal-cooled fast neutron breeder reactor (LMFBR) (*12, 13*) but are still significant in comparison with the quantity (on the order of 10 kilograms) required to make a simple fission explosive. The relatively low rate of fissile plutonium discharge for the once-through HTGR fuel cycle is striking, however. This is partly because of the large fraction of thorium in the fertile material of the HTGR fuel and partly because of the characteristically high burnup (*14*) of HTGR fuel, which results in a large fraction of the produced plutonium being fissioned in place before it is discharged. The rate of discharge of fissile plutonium from this HTGR system is so low that it is comparable to the expected 1 to 2 percent rate of loss from the plutonium breeder fuel cycle.

For closed fuel cycles it is still possible to preserve some of the proliferation resistance qualities on the once-through fuel cycles by recycling only isotopically denatured fissile isotopes. This can be done economically only in fuel cycles where the principal fertile material in the reactor fuel is thorium instead of ^{238}U. In such fuel cycles the artificial fissile isotope ^{233}U would be produced through neutron capture on ^{232}Th. Uranium-233, like ^{235}U, can be isotopically denatured for nuclear weapons purposes by mixing it with ^{238}U. Uranium-233 is ordinarily considered isotopically denatured when it is diluted below a concentration of 12 percent in a mixture of ^{238}U.

In a closed denatured uranium-thorium fuel cycle (see Fig. 1b), fresh reactor fuel would be a mixture of denatured uranium and thorium (*15*). The denatured uranium would be a mixture of recycled uranium containing both ^{233}U and ^{235}U and "makeup" uranium highly enriched in ^{235}U to compensate for the fact that the recycled uranium would be fractionally more depleted in fissile isotopes than in ^{238}U. Plutonium would not be recycled but instead would be either recovered and stored at the reprocessing plant or disposed of with the radioactive reprocessing waste. For ACR's the loss in fuel value would not be large since the rate of fissile plutonium discharge for these reactors operating on a denatured uranium-thorium fuel cycle is relatively low (see Table 1).

In terms of proliferation resistance the closed denatured uranium-thorium fuel cycle stands between the once-through fuel cycle and the plutonium fuel cycle (see Fig. 1). As with the once-through fuel cycle there is no chemically separable weapons-usable material in the fresh fuel, but as with the plutonium fuel cycle there is a weapons-usable material present at the fuel cycle facilities. These sensitive facilities, however, would have such large capacities (each would typically service 50 to 100 large power reactors) that they could be concentrated at a relatively few secure international centers (*16*).

Table 1. Uranium requirements and fissile plutonium discharge rates (for a 1-GWe reactor operating at a 65 percent average capacity factor). The U_3O_8 requirements pertain to the uranium mill. The tails stream at the enrichment plant is assumed to contain 0.1 percent ^{235}U. For enrichment priced at $75 per separative work unit, this tails assay becomes more economical than the 0.2 percent ordinarily assumed when the price of U_3O_8 reaches $60 to $70 per pound. Reprocessing losses in recycling systems are assumed to be 2 percent. The inventory is the U_3O_8 equivalent of the fissile material in the system (in the reactor and in the fuel cycle "pipeline") in excess of 3 years' makeup requirements for reactors which are refueled annually (LWR, LMFBR), 2 years' makeup requirements for reactors which are refueled continuously (HWR), and 2½ years makeup requirements for reactors which are refueled semiannually (U.S. HTGR). These inventories represent one-time capital investments that can be passed on to start up replacement reactors when a plant is retired.

Reactor type	Fissile enrichment of fresh fuel (%)	Core discharge burnup (Mwd/kg HM)	U_3O_8 requirements (tons)		Fissile plutonium discharge (kg/year)
			Inventory	Annual	
Low-enriched uranium, once-through					
1. LWR (PWR)	3.2	33	242	143	141
2. LWR (PWR)	4.4	55	286	120	98
3. HWR (CANDU)	0.7*	7.5	142	135	295
4. HWR	1.2	20.6	142	88	127
Denatured uranium-thorium, once-through†					
5. HTGR	8.5	125	242	91	22
Denatured uranium-thorium recycling					
6. LWR	4.8	35.6	706	86	52
7. HWR	1.7	16	610	30	26
8. HTGR	4.5	65	294	59	39
9. LMFBR	14.8	50	1755	87	350
Plutonium recycling					
10. LMFBR	13.6	75	‡	‡	1029

*Natural uranium. †The "denatured uranium" here is a mixture of fissile uranium isotopes and ^{238}U, such that the percentage of the fissile isotopes in the mixture is 12 percent when the fissile isotope is ^{233}U, 20 percent when the fissile isotope is ^{235}U, or the weighted average when both are present. For the denatured recycling systems it is assumed that plutonium is not recycled. ‡Not applicable.

Uranium Efficiency

Isotopic denaturing was our first criterion for evaluating fuel cycle alternatives. Uranium efficiency was our second criterion, and most of the alternative nuclear systems discussed in this article have annual uranium makeup requirements that are substantially less than those of the LWR operated on today's once-through fuel cycle. Table 1 shows that substantially improved uranium utilization efficiency is possible with current reactor types without the recycling of chemically separable weapons-usable material. The first five entries in the table are as follows:

1) The reference case, that is, the LWR operating on its current once-through, low-enriched uranium fuel cycle (*17*).

2) The projected results of the first stage of a program aimed at increasing the uranium efficiency of this once-through system. A 15 percent saving would be associated with an increase in the fuel burnup (*18*).

3) The Canadian heavy-water reactor (CANDU) operating on its currently used natural uranium once-through fuel cycle (*19*).

4) Projected results for the HWR, showing that its uranium efficiency on a once-through fuel cycle could be significantly improved if it were fueled with slightly enriched uranium. The uranium requirements for this ACR are only about 60 percent of those for today's LWR operating on a once-through fuel cycle (*20*).

5) The calculated uranium requirements of another ACR, the HTGR, operating on a once-through denatured urani-

um-thorium fuel cycle—about as low as those of the HWR on the slightly enriched uranium fuel cycle (*21*).

Improvements in uranium efficiency beyond those achievable in once-through fuel cycles can be obtained by reprocessing and fissile recycling. Table 1 also shows the savings predicted by current calculations for isotopically denatured uranium recycling in LWR's (*19*), HWR's (*19*), and HTGR's (*22*), without major reactor design modifications. The calculations for an LMFBR restricted to denatured uranium recycling show how much the performance of this system would be degraded by the denaturing requirement (*23*).

Since neutron-absorbing fission products build up in the fuel with increasing fuel "burnup," and since such neutron losses reduce the system's conversion ratio (the number of new fissile atoms produced by neutron capture on fertile atoms per fissile atom destroyed), the uranium efficiency can be increased by reducing the time spent by the fuel in the reactor. With current reactor types the uranium savings would not offset the extra costs of more frequent fuel reprocessing and refabrication until very high uranium prices were reached, but for nations concerned about the security of the uranium supply more frequent recycling could be a practical option. Indeed, on a nondenatured uranium-thorium fuel cycle the conversion ratios of the HWR, the HTGR, and the LWR can all be pushed to 1.0 (a break-even breeder) at recycling costs that may be economically practical (*24*). While reactor performance on a denatured fuel cycle would not be as good, it appears that for some ACR's, at least, the conversion ratio could be pushed close to 1.0.

Economics

At least until late 1975 the U.S. Atomic Energy Commission and its successor agency, the Energy Research and Development Administration (ERDA), were basing their civilian nuclear energy R & D program on the belief that, even if the price of uranium did not rise, the plutonium breeder would have a decisive economic advantage over the LWR operated on a once-through fuel cycle. This belief stemmed from the expectations that the capital cost of the LMFBR would decline to the same level as that of the LWR within 15 years after its introduction, and that its fuel cycle cost would be very much smaller than that for the LWR in 1974 (*25, 26*).

More recently, however, both the LMFBR capital and fuel cycle cost estimates have been revised upward by the U.S. Department of Energy (DOE), the successor agency to ERDA. The capital cost of a commercial LMFBR is now expected to be 25 to 75 percent greater than the capital cost of an LWR with the same generating capacity, and the expected costs for reprocessing and refabricating breeder fuel have risen to a level where, at today's uranium prices, they would roughly offset the savings in uranium and enrichment costs which the breeder would make possible [on the basis of 1977 DOE cost estimates (*27*)].

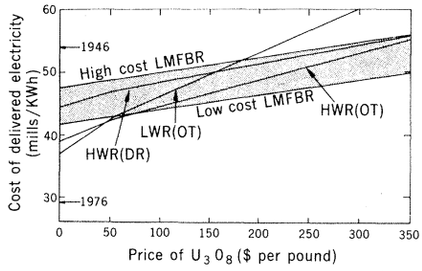

Fig. 2. Here the estimated cost of delivered electricity (in 1976 dollars) leveled over the life of the power plant is shown for alternative reactor systems as a function of the price of U_3O_8. Average electricity prices in the United States (in 1976 dollars) for the years 1946 and 1976 are indicated by arrows on the left-hand scale. Two once-through (*OT*) systems are shown here: the *LWR (OT)* and the *HWR (OT)* fueled with slightly enriched uranium. The *HWR (DR)* system involves denatured uranium recycling. A range of electricity costs for an LMFBR-LWR system is shown as a shaded band. This cost band corresponds to a nongrowing system of LMFBR's and the plutonium burning LWR's that could be supported with the excess LMFBR plutonium. The low and high sides of the shaded band correspond to LMFBR capital costs that are, respectively, 25 and 75 percent greater than the capital cost of the LWR. For the LWR and HWR fuel cycles the cost of electricity corresponds to 0.2 percent enrichment tails below \$60 per pound of U_3O_8 and 0.1 percent tails above \$60 per pound (hence the break in the slope of these curves at this uranium price).

As a result, the cost of electricity from an LWR operated on a once-through fuel cycle lies within the uncertainty band of the costs from an LMFBR system for U_3O_8 prices between approximately \$60 and \$180 per pound (Fig. 2). (Our LMFBR system includes approximately one LWR fueled with the excess plutonium generated by 2.4 LMFBR's of the same generating capacity.) For U_3O_8 prices below \$60 per pound the LWR appears to hold a clear advantage (U_3O_8 prices today are approximately \$40 per pound for new contracts; 1 pound of U_3O_8 = 0.38 kilogram of uranium); above \$180 per pound the LMFBR appears less expensive over the entire range of breeder cost uncertainty.

If U_3O_8 prices climb much higher than they are today, however, uranium-efficient ACR's will probably become economically competitive with the LWR. Also, because the cost of their electricity will be less sensitive to the price of uranium than that for the LWR, these ACR's will probably remain economically competitive with the LMFBR up to much higher uranium prices than will the LWR. For specificity we will illustrate the potential economic role of ACR's using the example of the Canadian HWR. Within the uncertainties of the economic and technical data it appears that similar cases could be made for the HTGR or an advanced LWR.

The capital cost of an HWR, including its heavy-water inventory, is likely to be considerably greater than that of the LWR. We take the capital charge per kilowatt-hour to be 20 percent higher than for the LWR (*27*). This makes electricity generated by the HWR more expensive than LWR-generated electricity at low uranium prices; but, by the time the price of U_3O_8 rises to \$60 per pound, the lower uranium and enrichment requirements of an HWR operating on a slightly enriched once-through fuel cycle would offset its capital cost disadvantage. As shown in Fig. 2, this system would then generate electricity at costs within the range of uncertainty calculated for the LMFBR system up to U_3O_8 prices of more than \$350 per pound.

The estimated cost of electricity from an HWR operating with denatured uranium recycling, although higher than that for the once-through fuel cycle, lies within the range of uncertainty of corresponding costs for electric energy from an LMFBR system over the full range of uranium prices shown. It is interesting that the cost of electricity from this HWR system rises only slightly more rapidly with the rising cost of uranium than the cost of electricity from the LMFBR system. The cost of electricity from the LMFBR system rises with the price of uranium because the investment required to purchase its large fissile inventory increases with the price of uranium (*28*).

The uranium requirements of ACR's operating with uranium recycling would be so low that cumulative uranium requirements would rise only very slowly once these systems were established. If the rate of change of the price of uranium depends on the rate of increase of cumulative consumption (because of cheaper ores being mined first), then the price of uranium will also rise relatively slowly: in the case of the HWR operating with denatured uranium recycling about 0.2 times as rapidly as with the LWR on

a once-through fuel cycle. The rate of increase in the cost of electricity generated by the HWR system caused by uranium price increases would be much slower—only 0.2×0.2 (= 0.04) times the rate of increase for the once-through LWR—because only 0.2 times as much uranium would be purchased per kilowatt-hour. Even for a once-through ACR system requiring 0.6 times as much uranium as a once-through LWR, the rate of increase in the cost of electricity generated by the ACR system would be only 0.6×0.6 (= 0.36) times as fast as the rate of increase for the LWR system.

Thus, an ACR, by reducing the rate of uranium consumption, would both slow down the rate of uranium price increases and be relatively insensitive to those increases which did occur.

A High Nuclear Growth Scenario

To test the viability of an evolutionary strategy even for a large U.S. economy heavily dependent on fission, we describe here a scenario in which by the year 2020 nuclear energy provides one-third of the primary energy consumed by a U.S. economy with a gross national product (GNP) larger by a factor of $2^1/_2$ than the GNP in 1975. For simplicity we assume that all of this fission energy is used to generate electricity.

The nuclear growth scenario which we derive is shown in Fig. 3. Nuclear power grows through 300-GWe installed capacity in the year 2000 to 640 GWe by 2020, after which it plateaus. The electric energy generated annually by the 640-GWe nuclear capacity operating at an average of 65 percent capacity corresponds to approximately twice the total electric energy generated in the United States in 1975 (1 GWe = 10^9 watts of electric power).

This is certainly a large fission economy by any of today's yardsticks, but it is small in comparison with the nuclear power growth projections that were being used to justify the LMFBR development program only a few years ago. As recently as 1975, for example, ERDA was projecting a U.S. nuclear economy exceeding 3700-GWe capacity by the year 2025. At that time, however, the art of projecting the growth of electric power consumption corresponded to very little more than projecting past exponential growth rates into the future. The ERDA "reference case" assumed a doubling of U.S. electricity consumption approximately every 13 years for the next 50 years with no indication of a plateau even at the end of that period (*29*).

It has now become clear that there are many trends that tend to damp out such rapid growth in the consumption of electric power. These include the end of the post-World War II "baby boom," an approach to saturation in the degree of electrification of the U.S. energy economy, and the transition from an era of declining to one of rising electricity prices. We take these effects into account.

The primary energy variable in this scenario is the total energy consumed in the economy, which is related to the level of economic activity, as measured by the (deflated) GNP, through an "energy efficiency" factor η:

$$E = GNP/\eta$$

Since 1970 η has increased at an average rate of 1.3 percent per year, reflecting deliberate improvements in the efficiency of energy use in response to increasing energy prices and expectations of a constrained energy supply in the future. If, as seems likely, U.S. energy prices (in constant dollars) continue to rise—perhaps doubling over the next 25 to 35 years—the average rate of increase in η will probably be at least 1 percent per year (*30*). We make this an assumption in our derivation [although it is less than half of the average rate of improvement which could be achieved if the barriers to implementing economically justified energy efficiency improvements could be overcome (*31*)].

The effect on GNP growth of population trends may be most easily discussed through a representation of the GNP as a product of two factors—employment (measured in terms of full-time equivalent employees, L) and GNP per worker (the average productivity, P):

$$GNP = L \times P$$

With this representation, approximately half of the average 3.5 percent annual rate of GNP growth experienced during the period 1950 to 1975 can be associated with the increased number of (full-time equivalent) workers born in the baby boom which ended in the late 1960's. Under the assumption that the U.S. fertility rate stops declining and stabilizes at 1.9 children per woman (slightly higher than the level of 1973 to 1977) and that net immigration continues at its average recent rate of approximately 400,000 per year, the growth in employment even in a "full employment" economy (4 to 5 percent unemployment) would average only 1 percent per year over the period 1975 to 2010 and would then begin to decline unless the fertility rate increased.

We assume that the average 1950 to 1975 rates of productivity growth for the goods and services sectors of the economy will continue for the next several decades. The overall average annual rate of growth in U.S. productivity would then be $1^1/_2$ percent in the period 1975 to 2010—half way between the very low level of 1.2 percent per year average growth rate for the period 1965 to 1975 and the long-term average of 1.8 percent per year for the period 1950 to 1975 (*32*).

As a result of these trends in employment and productivity, the U.S. economy would grow more slowly in the future than in the past, averaging $2^1/_2$ percent per year over the period 1975 to 2010. Per capita GNP in this period would grow at approximately the same rate as in the period 1950 to 1975, however.

If we add the assumption of a 1 percent average annual improvement in the energy efficiency of the overall economy, total annual U.S. energy use would increase at an average annual rate of $1^1/_2$ percent (or by a factor of 1.7) over the period 1975 to 2010. The rate of increase toward the end of this period would be less as the labor force plateaus. We assume in our nuclear growth scenario, however, that the nuclear power sector continues to grow rapidly after 2010 until it accounts for about one-third of U.S. total primary energy consumption and plateaus after 2020 at approximately 640 GWe. This plateau could come about either as a result of saturation of energy use and of electrification, with any further slow growth of the GNP largely offset by increases of the energy efficiency of the economy, or as a result of the penetration of new energy sources such as solar energy or fusion in a growing energy economy. At least one of these eventualities seems likely. In any case, our conclusions regarding an evolutionary strategy for nuclear power would not be significantly affected by continued slow growth in the nuclear sector after 2020.

Uranium Prices

The problem of the uranium supply for U.S. nuclear power plants is usually put in terms of the amount of time it will take a given projected nuclear capacity to consume an assumed U.S. resource base of a few million tons of U_3O_8. This formulation is not correct. The uranium resource base of the United States cannot be represented by a single number. As with other minerals it is an increasing function of price. At higher prices it becomes economic to mine lower grade and less accessible ores.

This point is particularly germane to our evolutionary strategy, because ACR's are likely to remain economically

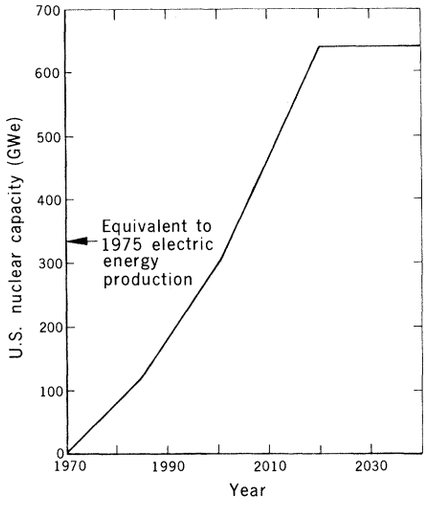

Fig. 3. If fission energy comes to play a major role in the future U.S. energy supply, its growth might look approximately as shown. Our results are not sensitive to the detailed form of the growth curve but would be undermined if electric demand continued to double indefinitely every 10 to 15 years—as was assumed until recently by most official studies. The capacity shown is for a nuclear system operating at an average 65 percent capacity factor. The plateau corresponds to a level of electrical energy production from nuclear power plants after 2020 almost twice as great as total U.S. electric energy production in 1975.

competitive with the LMFBR even if fueled from uranium resources much more costly than those which have historically been included in estimates of the U.S. uranium resource base. Our purpose here, therefore, is to lay out the basis for a conservative (in this case "reasonable lower bound") estimate of the cumulative availability of U.S. uranium as a function of price.

The 1977 uranium supply curve estimate by the Supply Evaluation Branch of the Division of Uranium Resources and Enrichment of DOE is shown in Fig. 4 (*33*). Below a price of $100 per pound this estimate includes principally the U_3O_8 which DOE estimates is recoverable in the United States at a forward cost of $50 per pound or less. (Forward costs do not include the costs of exploration, land acquisition, royalties, or profits and therefore are lower than prices by about a factor of 2 in this price range.) The official 1978 DOE estimate of resources in this category was 4.4 million tons of U_3O_8 (1 ton of U_3O_8 = 0.77 megagram of uranium) (*34*). At prices above $100 per pound the DOE analysts assumed that it would be possible to begin recovering U_3O_8 from the very large low-grade "Chattanooga" shale deposit which lies relatively near the surface under much of central Tennessee and adjacent areas of Kentucky and Alabama (*35*).

We also show in Fig. 4 a curve for a lower uranium supply. This curve, which was generated by the same DOE group, differs from the first mainly by including only reserves and estimated "probable" resources in as yet unexplored areas of known mineralization in known uranium districts. It is also somewhat more pessimistic regarding the costs of exploiting the Chattanooga shale. We will use the straight-line approximation to this lower supply curve shown in Fig. 4 as our "lower-bound" uranium supply curve in the discussion below.

Uranium is also available in substantial quantities as a by-product associated with the recovery of other minerals. Probably the most significant source of by-product uranium in the future will be from phosphate recovery (*36*). By-product uranium recovery is relatively inexpensive in this case since the uranium goes into solution when the phosphate is extracted as phosphoric acid. As a result of the rise of uranium prices in 1974 to 1975, by-product uranium recovery operations have begun in Florida, and it is estimated that the United States could be producing 8000 tons of by-product U_3O_8 annually by the end of the century (*37*). In our analyses we assume that by-product U_3O_8 will be available at a rate that increases linearly with time starting in 1980 until it stabilizes at approximately 8000 tons per year in 2000. The cumulative production of by-product U_3O_8 would amount to 0.32 million ton by 2030 and 0.72 million ton by 2080.

A Timetable for the United States

We are now in a position to address the question posed initially—whether the evolutionary strategy we propose represents a credible alternative to the LMFBR. We first consider the situation in the United States.

The critical components of the evolutionary strategy are first to continue to rely on once-through fuel cycles—shifting, however, as soon as practical to more uranium-efficient ACR systems; and second to develop the option to shift these same ACR's to denatured uranium recycling if for some reason the uranium supply becomes constrained.

Figure 5, which is based on the high nuclear growth scenario, shows in simplified form how such a strategy compares in terms of cumulative uranium requirements with the two extreme strategies ordinarily discussed: continued reliance on unimproved LWR's operating on a once-through fuel cycle (the top curve), and a shift to plutonium breeder reactors beginning in the year 2000 at the

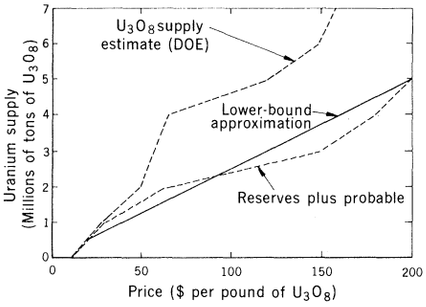

Fig. 4. The upper dashed line shows the 1977 DOE estimate of U.S. uranium resources as a function of the estimated equilibrium market price. The lower dashed line includes only identified reserves and estimated resources in the "probable" category (see text). The solid line represents the "lower bound" estimate on the availability of U.S. non-by-product uranium used in our analysis. In addition we assume that the recovery of uranium as a by-product of other mining operations rises to a rate of 8000 tons U_3O_8 per year by the year 2000.

maximum rate allowed by the availability of plutonium for start-up inventories (the bottom curve) (*38*). The two middle curves correspond to the two extreme variants of the evolutionary strategy: indefinitely continued dependence on the once-through fuel cycle and a shift in about the year 2000 to operation of all reactors on a closed fuel cycle with denatured uranium recycle. For specificity it has been assumed that the ACR's have the uranium requirements shown in Table 1 for the HWR.

In the curves associated with the evolutionary strategy it is assumed for computational simplicity that all reactors coming on line before the year 2000 are unimproved LWR's and that all reactors coming on line after the year 2000 are ACR's. Of course, in reality, the uranium efficiency of LWR's will be improved over the next decades and any transition to a new reactor type would be spread out over a period of at least a decade.

Each of the two uranium requirement curves associated with the evolutionary strategy is striking for a different reason:

1) It is 100 years before the cumulative requirements associated with a continued dependence on the once-through fuel cycle exceed the 4.4 million tons of U_3O_8 which, according to current DOE estimates, are available in high-grade uranium deposits. Even if one assumes that the uranium supplies are limited to the lower-bound approximation shown in Fig. 4, the price of U_3O_8 would be driven up to only $180 per pound during this 100-year period, a price which would still leave electricity generated by a once-through HWR system in the lower half of the breeder system cost range (see Fig. 2).

2) The phasing-in of ACR's and the introduction of denatured uranium recycle at the turn of the century would result in a reduction in cumulative uranium requirements over the next 100 years nearly as great as could be achieved with the deployment of a breeder system. Although the introduction of recycling would probably not be economically justified at such an early date, the cost of electricity delivered by this ACR system would still be well within the range of uncertainty calculated for the breeder system. After 2030, when the closed ACR system would be fully established, its uranium requirements would be so low that, even with the lower-bound uranium supply curve, the price of uranium would be increasing each decade by only $5 per pound and the associated increase in the cost of the electricity generated would be only 0.2 percent per decade.

It is important to note that it would be much easier to establish a closed fuel cycle for ACR's than for breeders because an ACR can operate economically on a once-through fuel cycle. Therefore, the ACR system could better tolerate delays or failures in reprocessing and refabrication facilities than the breeder system. Also it would be possible to wait until 50 to 100 GWe of ACR capacity had been deployed and economies of scale in fuel cycle facilities could be fully exploited before closing the ACR fuel cycle. In contrast, it would be necessary in the conventional breeder strategy to have a major reprocessing industry even before the first LMFBR went into operation. A full-sized (1500 megagrams of heavy metal throughput per year) reprocessing plant would have to be operated for half a year to provide the start-up inventory for each GWe of LMFBR generating capacity.

Thus it appears that, with the introduction of ACR's, it would be possible to have a large nuclear power system economically competitive with a breeder system for a century without a commitment to reprocessing. The possibility of shifting the ACR's to a very uranium-efficient, denatured uranium-thorium recycling system would provide an additional level of assurance that a very long-term reliance on these reactor types would be possible.

The Rest of the World

It is often argued that, while the United States may be able to postpone the commercialization of a breeder reactor, other nations less well endowed with indigenous resources of uranium and fossil fuel cannot afford to do so.

As Fig. 5 shows, however, the introduction of a uranium-efficient ACR operating with denatured uranium recycling instead of the breeder in the year 2000 would result in little change in cumulative U.S. uranium requirements before the middle of the next century. This result is not peculiar to the United States; indeed, the breeder would have a comparative advantage in this country in 2000 relative to many other nations, because the spent fuel from LWR's is creating a very large U.S. inventory of plutonium for starting up breeders.

Since closed-cycle ACR's can do about as well as the LMFBR in reducing uranium requirements till the middle of the next century, the uranium supply issue in the evolutionary strategy is transformed into the question of whether all nations could afford to continue to rely on ACR's operating on once-through fuel cycles in this period.

If uranium-poor nations were to continue to rely on such fuel cycles, they would have to import perhaps 50 percent more uranium over the next 50 years than would be necessary with a closed fuel cycle. For these nations the flexibility of the evolutionary strategy should be

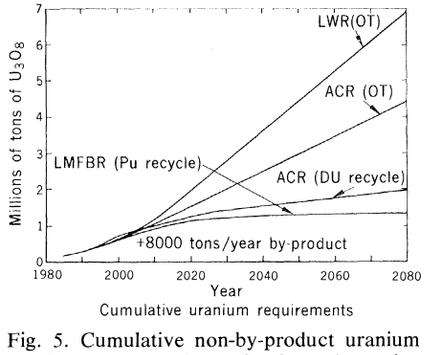

Fig. 5. Cumulative non-by-product uranium requirements are shown for four alternative U.S. strategies, given the growth in nuclear-generated electricity pictured in Fig. 3. The top curve [*LWR (OT)*] corresponds to continued operation of LWR's on the current once-through (*OT*) fuel cycle. The bottom curve [*LMFBR (Pu recycle)*] corresponds to the introduction of a plutonium breeder reactor beginning in the year 2000. For the middle two curves, all new reactors introduced after the year 2000 are ACR's; for specificity they are assumed to be HWR's. The curve labeled *ACR (OT)* corresponds to the continued operation of all reactors on a once-through fuel cycle indefinitely. (The HWR would be fueled with slightly enriched uranium.) The curve labeled *ACR (DU recycle)* shows how cumulative uranium requirements could be reduced substantially by shifting all reactors to denatured uranium-thorium recycling around the year 2000. All reactors are assumed to be replaced at the end of a 30-year life. All uranium inventory and annual makeup requirements for these alternative scenarios are those listed in Table 1 except it is assumed that before the year 2000 the tailings at the enrichment plant contain 0.2 percent ^{235}U.

appealing. As long as they can buy uranium at competitive market prices, continued reliance on once-through ACR systems would probably be the most economical course. If at some time the uranium supply situation appeared to be getting tight, however, the same ACR's could be shifted to a closed fuel cycle with extremely low uranium requirements. In addition, to guard against disruptions in the supply, uranium could be stockpiled. In contrast to the situation with petroleum, a stockpile of uranium adequate for many years could be maintained (as is already being done by some nations) for a low-cost penalty. For example, the carrying charge associated with a 10-year stockpile of slightly enriched uranium for an HWR operating on a once-through fuel cycle would add only 1.5 percent to the cost of a kilowatt-hour of electricity for U_3O_8 at $60 per pound. Balance-of-payment considerations are also relatively minor for uranium imports relative to petroleum imports. Taking again the HWR operating on the slightly enriched once-through fuel cycle as our example, the cost of U_3O_8 would have to rise to over $500 per pound before the fuel cost associated with the released fission energy would be as great as that for oil at $13 per barrel.

Conclusions

The plutonium breeder reactor has dominated the imagination (and research budgets) of the nuclear establishments of the industrialized countries for more than a decade—to the point where no other system has appeared practical or worthy of serious attention. Recently, however, this reactor has become controversial as the proliferation vulnerabilities of its fuel cycle have become increasingly evident and as its economics have begun to look less favorable.

In contrast, the evolutionary strategy described herein involves both simpler and more flexible ACR's which, unlike the LMFBR, can be operated economically on isotopically denatured fuel cycles in either the once-through or the recycling mode. Adoption of the evolutionary strategy would therefore enable the world to postpone for decades decisions regarding fuel reprocessing while nuclear power growth and uranium resource situations are clarified and the possibilities for a strengthened international safeguards regime are determined. If uranium supplies are found to be limited in some regions and arrangements can be agreed upon which make fuel cycles involving reprocessing sufficiently proliferation-resistant, then some of these con-

verter reactors could be shifted to denatured uranium-recycling operation.

Thus the evolutionary strategy would build on the familiar and encourage nuclear experts to focus during the next few years on making more efficient, safe, and secure the nuclear systems on which nations now rely instead of dissipating their talents devising safeguards for new systems which are likely to be inherently more vulnerable to the diversion of weapons-usable materials.

References and Notes

1. The Non-Proliferation Alternative Systems Assessment Program was established within what is now the U.S. Department of Energy after President Carter's decision in April 1977 not to continue the process of commercializing the plutonium fuel cycle in the United States. Forty nations agreed to establish a 2-year International Fuel Cycle Evaluation at a meeting in Washington, D.C., in October 1977.
2. U.S. Congress, *Nuclear Proliferation and Safeguards* (Office of Technology Assessment, Washington, D.C., 1977), appendix VI.
3. H. A. Feiveson, thesis, Princeton University (1972); A. Wohlstetter. *Foreign Policy* **55**, 88 (Winter 1976–1977).
4. H. A. Feiveson and T. B. Taylor, *Bull. Atom. Sci.* **32**, 14 (December 1976).
5. H. A. Feiveson, F. von Hippel, R. H. Williams, *An Evolutionary Strategy for Nuclear Power* (Rept. No. 67, Center for Environmental Studies, Princeton University, September 1978).
6. H. A. Feiveson, *Annu. Rev. Energy* **3**, 357 (1978).
7. Natural uranium contains 0.7 percent ^{235}U and 99.3 percent ^{238}U.
8. A converter reactor converts some fertile material into fissile material but is a net consumer of fissile material and, therefore, in the absence of a source of artificially produced fissile isotopes, requires a supply of ^{235}U. A breeder reactor is a net producer of fissile material and, therefore, after its initial inventory of fissile material has been established, a breeder reactor economy can grow at an annual rate of a few percent without an external supply of fissile material. The "fuel" of a breeder is therefore one of the fertile isotopes ^{238}U or ^{232}Th or a mixture of the two.
9. This is true despite recent advances in centrifuge and laser isotope enrichment technologies. The development of these technologies does raise significant proliferation policy issues, however [see, for example, A. S. Krass, *Science* **196**, 721 (1977)].
10. Although a fast neutron chain reaction can be sustained at somewhat lower concentrations of ^{235}U in such a mixture, the corresponding critical mass becomes so large that weapons designers consider it impractical for nuclear explosives purposes [see, for example, T. B. Taylor, *Annu. Rev. Nuclear Sci.* **25**, 407 (1975)].
11. Thorium (specifically the isotope ^{232}Th) and ^{238}U are the only two fertile isotopes which are relatively abundant in nature. The artificial fissile isotope ^{233}U (162,000 year half-life) is produced after neutron capture on ^{232}Th in a completely analogous fashion to the formation of ^{239}Pu (24,000 year half-life) after neutron capture on ^{238}U. Uranium-233 has an advantage over ^{239}Pu in slow neutron reactors because the average number of neutrons produced per slow neutron captured on ^{233}U is larger (by between 0.2 to 0.6) than the number produced from ^{239}Pu. The extra neutrons lead to an increased "conversion ratio" for the system, that is, a larger number of new fissile atoms produced per fissile atom destroyed by neutron capture. This can lead to a reduced requirement for "makeup" fissile material from the outside (ordinarily ^{235}U). For many once-through fuel cycles these uranium savings are not to be realized, however, because it is necessary to have a higher concentration of fissile material in thorium-based fuel than in ^{238}U to maintain the chain reaction, with the result that a large fraction of the fissile material remains unfissioned in the spent fuel.
12. For the LMFBR operating on a plutonium fuel cycle the in-core plutonium fissile inventory is 3190 kg, and the breeding ratio is 1.28 [based on Y. I. Chang *et al.* (*13*)].
13. Y. I. Chang, C. E. Till, R. R. Rudolph, J. R. Deen, M. J. King, *Alternative Fuel Cycle Options* (ANL 77-70, Argonne National Laboratory, Chicago, 1977), tables 5 and 6.
14. Burnup is measured in units of Mwd/kg HM [megawatt-days of fission energy released per kilogram of heavy metal (uranium plus thorium plus plutonium)] in the fuel.
15. This fuel cycle was first proposed by Feiveson and Taylor (*4*).
16. International Atomic Energy Agency, *Regional Nuclear Fuel Cycle Centers* (IAEA, Vienna, 1977); A. Chayes and W. B. Lewis, Eds., *International Arrangements for Nuclear Fuel Reprocessing* (Ballinger, Cambridge, Mass., 1977).
17. For specificity we have assumed the most common type of LWR—a pressurized water reactor (PWR). LWR's are currently operated at a considerably lower uranium utilization efficiency than is indicated by the design value in Table 1. One reason is that U.S. enrichment plants are now operated with the depleted uranium "tails" still containing 0.25 percent ^{235}U versus the 0.1 percent assumed in Table 1. Another is that LWR fuel often does not reach its design burnup.
18. C. E. Till and Y. I. Chang, *Once-Through Fuel Cycles* (RSS-TM-13, Argonne National Laboratory, Chicago, 1978), table 1.
19. C. E. Till, "Fuel cycle options and fueling modes" (Argonne National Laboratory, Chicago, 9 January 1978, unpublished). See also E. Critoph, "The thorium fuel cycle in water-moderated reactor systems," paper presented at the International Conference on Nuclear Power and its Fuel Cycle, Salzburg, May 1977 (IAEA-CN-36/177, International Atomic Energy Agency, Vienna, 1977). All the HWR cases in Table 1 have been put on a common basis corresponding to a reactor with a 30.5 percent thermal-electric conversion efficiency.
20. C. E. Till and Y. I. Chang, *CANDU Physics and Fuel Cycle Analysis* (RSS-TM-2, Argonne National Laboratory, 1977), table 12. See also (*18*).
21. R. F. Turner, "Optimization of MEU/Th cycles for HTGR" (General Atomic Co. memorandum, 26 July 1978). See also E. Teuchert, *Once-Through Cycles in the Pebble Bed HTR* (Juelich Nuclear Research Center, West Germany, 1977).
22. R. F. Turner, personal communication.
23. For the LMFBR operated on a denatured fuel cycle, a linear combination of two oxide-fueled reactors (one of which is fueled with denatured ^{233}U and one of which is fueled with denatured ^{235}U) is taken such that the net production rate of ^{233}U is zero. The numbers have also been changed to correspond to an LMFBR with 40 percent thermal-electric efficiency [from the 35.5 percent used by Chang *et al.* (*13*)].
24. J. B. Slater, *An Overview of the Potential of the CANDU Reactor as a Thermal Breeder* (Chalk River Nuclear Laboratories, Canada, 1977); H. J. Rütten, C. E. Lee, E. Teuchert, *The Pebble-Bed HTR as a Net-Breeding System* (Rept. No. 1521, Juelich Nuclear Research Center, West Germany, 1978); and *Final Environmental Statement on the Light Water Breeder Reactor Program* (ERDA 1541, Energy Research and Development Administration, Washington, D.C., 1976), sect. II-E.
25. For the breeder cost numbers, see *Final Environmental Statement on the Liquid Metal Fast Breeder Reactor Program* (ERDA-1535, Energy Research and Development Administration, Washington, D.C., 1975), figure III F-19 and p. III F-77.
26. For the LWR fuel cycle cost numbers, see *The Nuclear Industry, 1974* (WASH 1174-74, U.S. Atomic Energy Commission, Washington, D.C., 1974), p. 20.
27. For a more detailed documentation of our economics calculations, see Feiveson *et al.* (*5*). Most of our cost figures are based on D. R. Haffner, R. W. Hardie, R. F. Hamburg, *An Evaluated Uniform Data Base for Use in Nuclear Energy Systems Studies* (Hanford Engineering Development Laboratory, Hanford, Wash., October 1977). One change that we have made is to raise the capital costs for an LWR from $625 to $800 per kilowatt of electric generating capacity, on the basis of the analysis of C. L. Rudasil [*Coal and Nuclear Generating Costs* (EPRI PS-455-SR, Electric Power Research Institute, Palo Alto, Calif., 1977)]. Other nuclear power plant capital costs have been increased by the ratio of these two costs. The principal reason for the high LMFBR capital cost is the use of sodium instead of water as a coolant. Because sodium is extremely reactive chemically, it is necessary to design special features into the system to keep the sodium isolated from air (a hermetically sealed refueling machine and an inert gas atmosphere surrounding the reactor plumbing system) and water and to limit the consequences of these sodium leaks which will inevitably occur (secondary sodium loops to carry the heat from the radioactive primary sodium coolant to the steam generators, guard vessels, containment purge systems, and complex steam-generator designs, for example).
28. The plutonium-fueled LMFBR and the plutonium-fueled LWR each have inventories of approximately 5000 kg of fissile plutonium (including the inventory outside the reactor in the fuel cycle). We find the market price of this plutonium relative to the price of U_3O_8 by setting the cost of electricity from a plutonium-fueled LWR equal to the cost of electricity from a uranium-fueled LWR. For consistency we assume in this comparison that the spent fuel from the uranium-fueled LWR is reprocessed for recovery and sale of its plutonium and that the recovered uranium is recycled. (The plutonium-fueled LWR of course operates on a closed fuel cycle.) In this way we find the following relation between C_p, the price of fissile plutonium in dollars per gram, and C_u, the price of U_3O_8 in dollars per pound:

$$C_p = 5.62 + 0.337\ C_u$$

29. See (*25*, table III F-7).
30. See, for example, E. L. Allen, C. L. Cooper, S. C. Edmonds, J. A. Edmonds, D. B. Reister, A. M. Weinberg, C. E. Whittle, L. W. Zelby, *U.S. Energy and Economic Growth, 1975–2010* (ORAU/IEA-76-7, Institute for Energy Analysis, Oak Ridge, Tenn., 1976); and Demand and Conservation Panel of the National Academy of Sciences Committee on Nuclear and Alternative Energy Systems, *Science* **200**, 142 (1978).
31. M. H. Ross and R. H. Williams, *Energy and Economic Growth*, study prepared for the Subcommittee on Energy of the U.S. Congress Joint Economic Committee (Government Printing Office, Washington, D.C., 1977).
32. Here the service sector is defined as services, government, communications, finance, insurance, and real estate, as these industries are defined by the Office of Business Economics, U.S. Department of Commerce. The goods sector is everything else. During the period 1950 to 1975 the productivity growth rates for these sectors were 2.4 percent per year for goods and 0.9 percent per year for services. During the same period the fraction of the gross product originating (GPO) in the goods-producing sectors declined at an average annual rate of slightly less than 0.2 percent (see National Income and Product Accounts in U.S. Department of Commerce, *Survey of Current Business*, various issues). We assume that the fraction of GNP associated with goods production continues to decline at this rate, that is, that the greater growth in productivity in the goods sector will continue to be slightly more than offset by the more rapid growth in service-sector employment.
33. The price represents the cost of production of the highest cost resource being mined at the corresponding cumulative production level plus a 15 percent rate of return on investment, and includes the production-constraints that would be associated with a nuclear economy growing through 450 GWe in the year 2000. It includes the 0.34 million tons of by-product U_3O_8 which are assumed to be producible by 2040 (G. F. Combs, Jr., personal communication).
34. U.S. Department of Energy, *Statistical Data of the Uranium Industry* [GJO-100 (78), Grand Junction, Colo., 1978].
35. A recent U.S. Bureau of Mines compilation of data for an area of 7000 square kilometers underlain by Chattanooga shale shows that the uppermost (Gassaway) member of the deposit averages 60 to 70 parts per million of U_3O_8 in a layer 3 to 5 meters thick. The corresponding estimate of in-place uranium resources is 4 to 5 million tons of U_3O_8 [U.S. Bureau of Mines, *Uranium from Chattanooga Shale* (Information Circular 8700, Washington, D.C., 1976).]
36. Uranium is commonly present at concentrations of 50 to 200 ppm in marine phosphorite rock, the source of most of the world's phosphate fertilizer [J. B. Cathcart, *Uranium in Phosphate Rock* (Open File Rept. 75-321, U.S. Geological Survey, Washington, D.C., 1975).]
37. J. Klemenic and D. Blanchfield, "Production Capability and Supply," Contribution to the Uranium Industry Seminar, October 1977 (U.S. Department of Energy, Grand Junction, Colo., 1977).
38. The LMFBR in this scenario has the characteristics given in Table 1 and in (*13*). We assume that all plutonium generated in LWR's is saved to start breeders until the equilibrium breeder generating capacity is reached. We assume that after 2000 all uranium recovered from LWR fuel is recycled in LWR's. In equilibrium the LMFBR capacity totals 392 GWe, the LWR capacity fueled by LMFBR generated plutonium totals 163 GWe, and the by-product uranium-fueled LWR capacity (assuming both uranium and plutonium are recycled) totals 85 GWe.

39. This research was supported by a grant from the Ford Foundation.