Nuclear power and nuclear-weapons proliferation

The danger that fissile isotopes may be diverted from nuclear power production to the construction of nuclear weapons would be aggravated by a switch to the plutonium breeder—but future uranium supplies are uncertain.

Ernest J. Moniz and Thomas L. Neff

For decades, nuclear power has been considered a major component in the energy supply plans of some countries and an important option for the future in others. Like other energy sources, especially oil, nuclear power has become linked to national security and economic health in many countries; the magnitude of fuel reserves and the assurance of supply have become issues of intense international concern. However, nuclear power raises an additional issue: its potential for contributing to the acquisition of nuclear weapons by nations or even by terrorist groups. The goals of adequate energy supply and nuclear-weapons nonproliferation are therefore potentially in conflict.

Proliferation risks differ with the forms of nuclear technology, and the political and technical opportunities for international control vary for different fuel cycles. Nuclear power reactors in the United States and in most other countries now operate on uranium enriched to about 3% in the fissile isotope U^{235} (see the Box on page 51 for a brief description of fissile materials and fuel-cycle technology), and such fuel can not be used in a nuclear weapon without further isotopic enrichment. Commercial enrichment, which demands very advanced technology, is still restricted to a few supplier countries and has not contributed directly to weapons proliferation.

On the other hand, the vigorous international pursuit of advanced fuel-cycle technologies has stimulated serious concerns about increased proliferation risks. One source of concern would be widespread deployment of *isotopic-enrichment* technologies, such as gas centrifuges. Another arises from the long anticipated worldwide shift to *plutonium* fuels, first in thermal reactors of the type now operating and eventually in fast breeder reactors. Plutonium is bred from U^{238} during reactor operation and, if chemically separated from the spent fuel, can be used to extend naturally available nuclear fuels. Pilot plants built to gain experience for future commercial activities could be immediate sources of weapons material, as the basic technology of plutonium separation is, unlike enrichment, known and widely published.

These concerns have led to extensive reexamination of the technical, economic and political assumptions underlying both national and international nuclear policies. In the United States several extensive studies of nuclear-power issues[1–3] have been completed within the last year, while an International Nuclear Fuel Cycle Evaluation involving more than 40 nations will take place over the next two years.

There is yet little agreement on the balance between energy benefits and proliferation risks associated with different fuel-cycle choices. This lack of agreement stems from differing views of proliferation risks and from wide variations in the energy supply and the security problems of different nations. The resolution of these differences will be largely a political process, and we do not pretend to offer solutions in this article. However, we will seek to clarify the basic technical and political issues, and to set forth the connections between various fuel cycles and their possible proliferation risks.

Fissile materials that can, in principle, be used to make nuclear weapons are present in all nuclear fuel cycles, in quantities large compared to the amount needed for making explosives. The ease with which such material can be recovered for weapons use, however, varies greatly with fuel cycle. Uranium and plutonium fuels differ in this regard: The former can be isotopically denatured, the latter can not. The thermally fissile isotopes U^{233} and U^{235}, when diluted to isotopic content less than 15–20% with U^{238}, can not be used in a nuclear weapon, because sufficiently rapid supercritical assembly becomes impractical. This rapid increase of critical mass with decreasing U^{235} isotopic fraction is indicated in the figure on page 44.

Uranium versus plutonium

For plutonium, on the other hand, the critical mass of any isotopic composition is quite small, as this figure also shows, so weapons material can be obtained by chemical rather than isotopic separation. Plutonium with thermally fissile Pu^{239} content greater than 93% is generally defined as "weapons-grade," but reactor-grade plutonium, with a fissile content of about 60–70%, has a critical mass only a factor of two greater. This does not mean that an efficient, high-yield explosive is manufactured easily with reactor-grade plutonium. In particular, Pu^{240} creates a substantial neutron background because of spontaneous fission, and premature initiation of the chain reaction is apt to occur. However, an explosion will still result—and the yield from a nuclear "fizzle" can be extremely large compared with that from conventional explosives.[3]

The plutonium-bearing spent fuel from the uranium cycle, intensely radioactive from fission-product activity, requires remote-handling facilities for any subsequent processing. If the plutonium is

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0031-9228/78/3104-0042 $0.50

recycled, the fission products would be removed during reprocessing, and this would eliminate the greatest technical barrier to diversion of plutonium from the fuel cycle to weapons use. Enrichment technology is tightly held by a few technologically advanced nations, and developmental research programs or direct technology transfer would be needed to diffuse this technology. On the other hand, many nations are now able to construct pilot-scale fuel-reprocessing plants, which provide plutonium suitable for weapons. India demonstrated this capability, and the capacity to construct a nuclear explosive clandestinely, in setting off a nuclear explosion in 1974, shown in the photos on pages 46 and 47.

Given the possibility of increased security risks arising from the adoption of plutonium fuel cycles, it is important to review their potential benefits critically, as these will determine the extent and rate of national commitments to plutonium use. The most obvious benefit of recycling is resource extension; the lifetime uranium requirements of light-water reactors are reduced by about 32% if the uranium and plutonium in the spent fuel are recycled. For an expanding reactor system this reduces to perhaps 20–25% in the US over the next few decades.[2] With current uranium prices, recycling would increase or decrease the cost of electricity by at most a few percent.

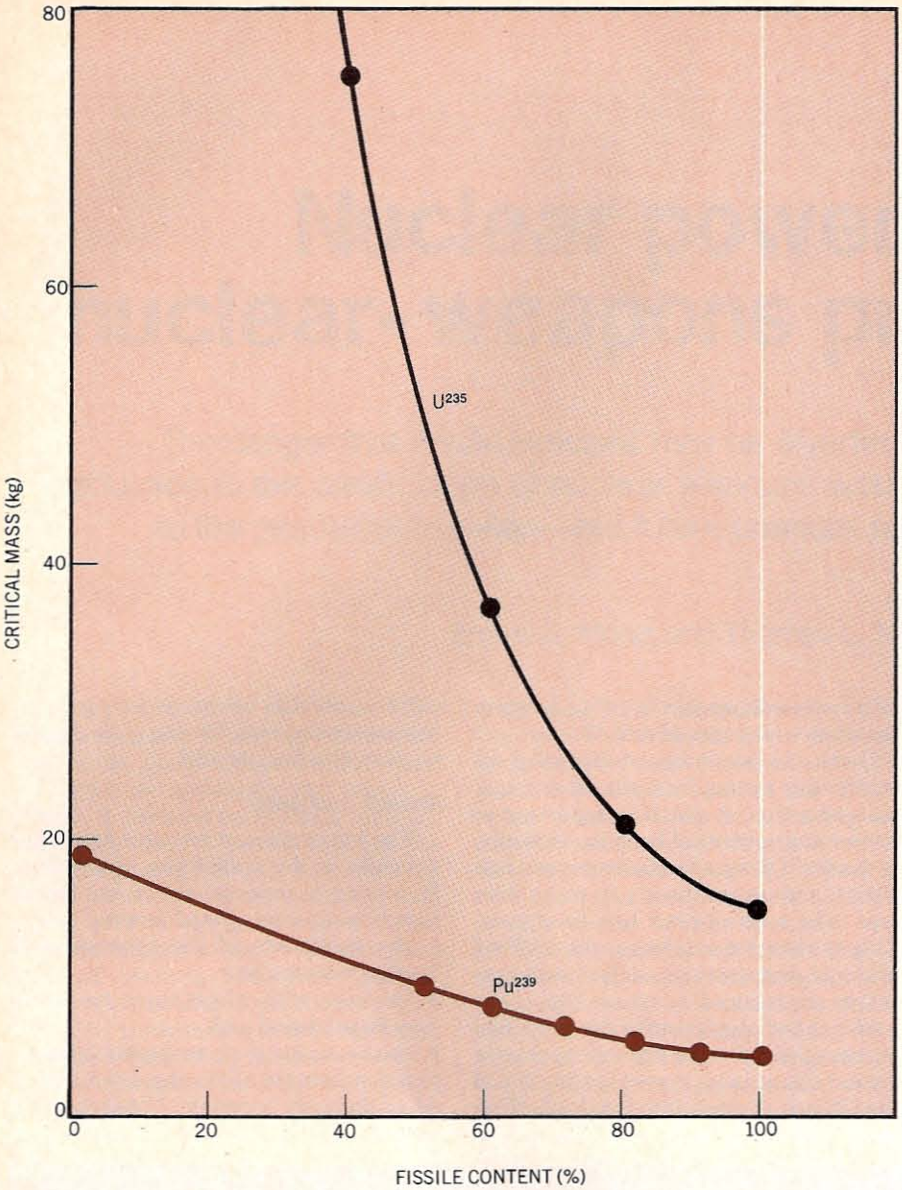
Enough uranium?

The importance of resource extension depends on the availability of uranium. A country's concern about its future supply centers on several factors:

- the magnitude of the domestic and foreign resource base,
- the ease with which these resources may be produced and
- secure access to an equitable international system for allocating uranium.

All of these are uncertain. Projections of

Reprocessing plant in limbo. The completed separation and UF_6 facility awaits licensing to begin operations, but the Nuclear Regulatory Commission has terminated the study on which this decision depends. The operators of the Barnwell, S.C. plant, Allied-General Nuclear Services, are seeking to turn the plant over to the US government. Nuclear-fuel reprocessing is likely to aggravate the risk of weapons proliferation.



The critical masses of uranium and plutonium as functions of fissile content. The two metals are in the form of spheres enclosed in thick neutron reflectors of natural uranium. The rapid increase in its critical mass makes isotopically dilute uranium unusable as a bomb. This is not so for plutonium, making it a greater proliferation hazard. Data from Theodore Taylor, Ann. Rev. Nucl. Sci. **25**, 407 (1975), and derived from a personal communication by Robert Selden.

low-cost uranium resources, summarized in table 1, are based upon sketchy data. Uranium appears in many geological environments, and exploration has been limited by periodically unhealthy conditions in the industry. Estimates of uranium availability at costs higher than the $30 a pound used in the table are even more uncertain, but some projections of $100-a-pound uranium range as high as 13 million tons.

There is considerable controversy about the meaning of these projections for long-term planning. If we accept such projections as upper bounds on producible uranium, use of this rapidly depleting resource would be increasingly unattractive. On the other hand, resource economists view the uranium industry as immature and contend that, as with other minerals, new reserves and lower-grade deposits will be produced on demand.[1] It is not yet clear which of these perspectives will prove correct.

For some decisions the present information is adequate. For example, a conservative projection of low-cost uranium available[4] in the US (about 1.9 million tons of U_3O_8) shows that there is at least enough uranium to supply the lifetime requirements (of 30 years at 65% capacity) of light-water reactors with approximately 350 GWe of capacity; the current projection for installed capacity in the year 2000 is 380 GWe. Consequently, resource considerations alone do not appear to require plutonium recycling during the next two decades.[1,2] However, recycling may be more attractive in countries without indigenous uranium and with a perceived insecurity of access to external supplies.

Uncertainties in long-term uranium supplies make it difficult to plan long-term research and development programs for new nuclear technologies. For example, the plutonium breeder would use resources at least 30 times as efficiently as current reactors. However, there would be economic penalties if uranium prices had not risen enough to overcome the additional capital cost. The potential social penalties that argue against early commitments will be discussed below. The rate at which uranium resources are discovered and consumed also has a bearing on opportunities for introducing advanced converter reactors or alternative breeders.

The problem of nuclear wastes is another element in the debate over early reprocessing and recycling. Because plutonium is a major source of radioactivity in wastes after about 500 years, some have concluded that reprocessing and subsequent "burning" of the plutonium is an important waste-management step. However, recent studies[1,2] reject this view. Only a small reduction of long-term actinide activity can be accomplished in this way, and the efficacy of long-term geologic isolation of the wastes is not demonstrably dependent on waste form.

Thus far we have focussed on the uranium light-water cycle with low enrichment and recycling of the plutonium extracted from the spent fuel. This path, usually seen as leading eventually to the plutonium breeder, has received by far the greatest research and development effort throughout the world. However, alternative fuel cycles might be preferable for reducing proliferation hazards. More efficient "once-through" cycles would diminish the pressure for moving ahead to plutonium breeders. Such cycles, especially those based upon thorium, might be more amenable to international measures for reducing access to weapons material. We shall discuss some of these more specifically in dealing with strategies for control of fissile material.

In table 2 we list several thermal-reactor options and their associated lifetime uranium commitments. Note that large resource extensions are possible; for example, modification of reactors for "spectral-shift operation" with thorium fueling can reduce ore requirements by more than a factor of two. In spectral-shift operation, the cooling system of the reactor is modified to include both light and heavy water, with the ratio of D_2O to H_2O decreasing through a fuel-burn cycle. However, except for the natural-uranium heavy-water reactor, CANDU, now operated in Canada, these alternatives are not yet ready for widespread commercial use.

Proliferation risks

Proliferation risks resulting from expansion and evolution of nuclear-power systems should be evaluated in the context of alternative routes towards weapons capability. Some have argued that there are no essential connections between the development of nuclear power and of weapons, because countries deciding to acquire nuclear weapons could achieve these capabilities through facilities dedicated to that purposes. For example, a uranium-enrichment program, free of commercial demands, could use comparatively simple means to support a very small weapons program. More likely would be construction of a plutonium production reactor fueled by natural uranium and an associated reprocessing plant; the design and operating characteristics for both are openly available. These dedicated routes would yield weapons material of higher quality than would be obtained by diversion of commercially produced plutonium, though several years would be required to construct and use dedicated facilities.

However, the widespread use of enrichment facilities, highly enriched uranium or plutonium fuels may alter drastically the political context of weapons-acquisition decisions in several ways:

- Countries deciding to develop weapons could use such fuel-cycle steps as a cover for the most time-consuming and detectible phase of a weapons program—the acquisition of fissile material.
- The scale of a weapons program fed by fissile material from a commercial fuel cycle could be much greater than that deriving from dedicated facilities.
- Many countries could move very close, in time and technical capability, to weapons without having to make and sustain the kind of political decisions required for dedicated programs.

What would be necessary to make a transition from non-weapons to weapons status rapidly—within a few days or weeks—would be preparatory steps involving weapons design and ancillary technical development, all of which are allowed under current agreements and may be conducted relatively easily in secret. This "latent" proliferation can adversely affect international relationships: For example, the possibility that a nation has made such preparation could pressure potential adversaries to do the same.

The risks associated with terrorists or other "subnational" theft are also greatly magnified by plutonium recycling. Stringent security measures are needed from the time plutonium is separated from fission products at the reprocessing plant until it is inserted back into the reactor as part of fresh fuel. There is considerable disagreement about the ability of a subnational group to construct a reliable, effective nuclear explosive. Nevertheless, there is consensus that a small competent group, given enough time, would have a reasonable probability of obtaining a significant yield.[3] This risk is clearly sufficient to warrant extensive safeguards for the control of plutonium in the fuel cycle.

Strategies for limiting proliferation risks must take into account not only the nature of the risks involved but also the technical and political opportunities for dealing with them presented by different fuel cycles. In the next decade, fuel-cycle choices are limited to natural uranium, uranium of low enrichment and recycled plutonium. The problem of theft by a subnational group and diversion by a nation are quite different, and deserve separate consideration.

Safeguards against theft

Safeguards against subnational theft include physical security and technical measures intended to deter theft, to increase the chance of detection if it occurs, and to make weapons fabrication more difficult and time-consuming. With plutonium recycling the most vulnerable points for covert diversion are at the reprocessing and mixed-oxide-fabrication plants, while the transportation links between these plants and the reactor might be targets for overt theft.

Physical security measures might include armed guards, massive transportation casks and special communications during transportation and surveillance, tightly controlled access to process streams and storage areas at reprocessing and mixed-oxide-fuel fabrication plants. These measures are qualitatively similar to those used in the protection of other valuable or dangerous commodities.

Technical measures aimed at complementing and reinforcing physical security include isotopic accountability schemes and fuel-form modification, specifically suited to the control of nuclear materials.

- In the accountability approaches neutron and high-resolution gamma-ray measurements monitor accurately the flow of fissile materials through the facilities. Under development are systems in which the measuring devices are coupled to a central computer for real-time analysis. Such accounting is complicated by the great variety of physical and chemical forms in which plutonium appears in process and waste streams. Fortunately, accurate accountability is achieved most easily at the same fuel cycle points at which the fissile material is most accessible for diversion, and automated accountability systems may therefore be important in maintaining security over the lifetime of a fuel-cycle facility. Such systems are not yet available.
- Fuel-form modification could involve pre-irradiating, "spiking" with radioactive isotopes (to make theft and subsequent handling more dangerous), incorporation of intense neutron sources (complicating weapons design), or dilution of plutonium with uranium (to force chemical processing of the material).

Although none of these measures can prevent misuse of fissile material, they can significantly complicate matters, and so gain time for the recovery forces after a theft. Because these measures must be consistent with the safe normal operation of the fuel cycle, the simple dilution approach is particularly attractive. Dilution can be be accomplished by mixing after processing or preferably, by adjusting the reprocessing chemistry so that plutonium and uranium are processed together and therefore never completely separated.

These measures for plutonium fuel cycles do entail additional fuel-cycle costs. For example, "coprocessing" results in the need to handle substantially larger quantities of plutonium-bearing materials and somewhat complicates mixed-oxide-fuel fabrication. Political and social costs are also involved, including the impact of security measures on the civil

Table 1. Estimated uranium resources recoverable at \$30/lb (1000 short tons U_3O_8)

	Reserves	Reasonably assured[b]	Estimated additional[c]
United States[a]	680	1090	1600
Canada		218	510
Africa		500	160
Europe		520	140
Australia		430	100
Asia		60	30
South America		40	60
		3538	2600

a. Estimated reserves and resources available at less than \$30/lb forward cost. Figures, from reference 4, do not include byproduct uranium from phosphate production.
b. For the US, the figure is for probable resources; elsewhere, the figures are for U_3O_8 at less than \$30/lb from *Uranium Resources, Production and Demand*, OECD-NEA/IAEA (1975), updated for Canada by R. Wright (Uranium Industry Seminar, DOE-GJO-108 (1977).
c. For the US, the figure is for possible and speculative resources; elsewhere, figures are from the OECD-NEA/IAEA report.

rights of workers in the nuclear industry.

The economic costs involved in implementing physical security are certain to be small compared to the overall cost of nuclear-generated electricity.[5] However, the cost/benefit calculation is made difficult by the unquantifiable nature of the threat and by the difficulty of agreeing on what constitutes an "acceptable" level of risk. In the US, this determination awaits the establishment of safeguards performance criteria by the Nuclear Regulatory Commission.

Strategies for international control

Safeguards play a somewhat different role in inhibiting national proliferation than in restraining subnational theft. The physical security and other measures relied upon in meeting the threat within a country are largely ineffective in dealing with national risks, because governments not only have control of nuclear facilities and materials but also have considerable resources for overcoming physical barriers to access to fissile material. Consequently, safeguards against national proliferation involve very important political components and operate primarily through the threat of detection and subsequent international response. Three elements are essential: an appreciable chance of detection, suitable international response mechanisms and time to respond before completion or use of weapons.

International safeguards are now based on a combination of bilateral constraints imposed by suppliers, and an international safeguards system administered by the International Atomic Energy Agency, a United Nations affiliate agency. The IAEA safeguards regime implements the surveillance function agreed to by the more than 100 nations that have ratified the Non-Proliferation Treaty. Bilateral constraints include restrictions on transfers—and subsequent retransfers— of nuclear technologies and materials. Efforts by supplier governments to achieve greater uniformity in these restrictions, particularly in the export of sensitive facilities such as reprocessing plants, resulted in the formulation of common supplier guidelines late in 1977. These partially extend IAEA safeguards to other countries.

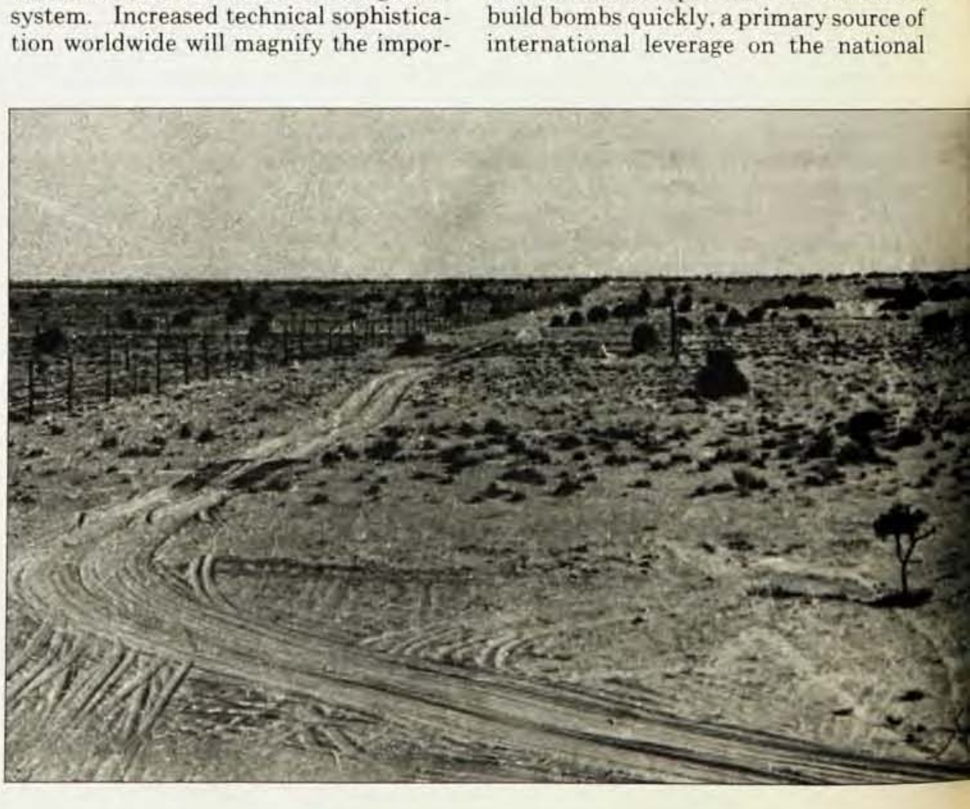
Safeguards are far from universally applied. As an intrusion into national sovereignty, IAEA inspection is sometimes resisted. Even with treaty-signatory countries, IAEA inspectors do not have access to the cascade area of enrichment plants.[3] A number of countries have refused to sign the Non-Proliferation Treaty, citing the inequality it institutionalizes between weapons and non-weapons states and the sacrifice of national sovereignty involved.

The technology and procedures of safeguards are also imperfect: Inspections have at times been infrequent and lacking in accuracy at the levels desirable; they are subject to human failures, do not involve real-time monitoring of nuclear activities and vary considerably between countries. Furthermore, the international process by which detection of diversion or misuse could be verified and brought to the timely attention of the international community is uncertain in its efficacy. Despite these problems, the present safeguards regime has been successful in the sense that misuse of fissile materials in the once-through uranium fuel cycle has not occurred. On the other hand, the opportunities for misuse have been rather limited.

Diffusion of technology and technological change present major challenges to the continued success of the safeguards system. Increased technical sophistication worldwide will magnify the importance of international monitoring of all nuclear facilities. The greatest challenge comes from the spread of enrichment and plutonium-separation technologies. While there is little experience with enrichment plants in non-weapons states, technologies requiring a large number of stages—gaseous diffusion and aerodynamic nozzle—appear to offer the best opportunities for safeguards, especially if direct inspection of the cascades is allowed. Technologies with fewer stages—gas centrifuges and eventually lasers—present greater problems, because high enrichment can be achieved more easily.

Restrictions on the export of these high-technology devices could effectively close off this route to weapons for many years in all but a few advanced nations. However, there is disagreement between some consumer and supplier states as to whether such a policy is consistent with the obligations of suppliers under the Non-Proliferation Treaty: The consumer states emphasize the supplier pledge to provide technology, while some suppliers say that to provide sensitive technologies is inconsistent with their overall Treaty responsibilities.

Plutonium fuel cycles also magnify the problems of detectibility and response time, because of the large amounts of potential weapons material involved and its relatively quick accessibility. Considerably more intrusive, and hence politically sensitive, international controls would be needed. Resident inspectors and automated internationally monitored real-time accountability systems have been proposed but these proposals have serious inherent limitations in preventing national diversion. If utilization of plutonium fuels makes it possible for countries to build bombs quickly, a primary source of international leverage on the national



India tests a bomb. The sequence shows the landscape before the explosion, the mound rising seconds after, and an aerial view of the crater. The 1974 underground test emphasized worldwide concerns that the spread of nuclear power technology would hasten the entry of additional nations to the nuclear club. Photographs courtesy of the Consulate General of India, New York.

proliferation problem would be undermined. The ultimate ability of safeguards to deal with these problems is still very uncertain.

Internationalization of fuel-cycle activities has been widely discussed as potentially fruitful in curbing latent proliferation. The basic idea is that all enrichment, reprocessing and fuel fabrication take place in internationally or regionally operated fuel-cycle centers so as to reduce the opportunities for any nation to divert fissile material and to enhance assurance of fuel-cycle services. Although there are formidable political realities to be confronted in establishing such centers, there are also incentives, such as fuel assurance, which may help to overcome these barriers.

Alternative fuel cycles

Alternative fuel cycles may provide a way to avoid some of the proliferation problems associated with use of plutonium fuels. A primary nonproliferation requirement for such cycles is that they minimize the presence of separated, or easily separable, weapons-usable material. There are a number of fuel cycles that satisfy this requirement, including the presently used cycle. Within the next two decades it would be possible to use once-through fuel cycles optimized for uranium and thorium utilization. These include light-water reactors modified for spectral-shift operation and thorium fueling, as well as modifications of the CANDU reactor. Beyond the next decade it may be possible to deploy once-through high-temperature gas-cooled reactors operating on moderately enriched uranium (20% or less) and thorium. Use of such cycles would help stretch fuel resources without appreciably increasing proliferation risks and buy time for possible development of proliferation-resistant longer-term recycle fuel cycles, for developing uranium resources and for international institutional changes allowing safer use of advanced cycles.

If nuclear power is to contribute to energy production in the long term, it will be necessary to turn eventually to reprocessing and recycling for high conversion or breeding rates. The U^{233}–thorium cycle offers an alternative to the uranium–plutonium cycle, with both substantial resource extension and enhanced opportunity for international safeguards control.[6] National reactors would operate on denatured fuel, containing about 15% fissile uranium. The spent fuel would contain some plutonium and so reprocessing would be under international control. Plutonium production is substantially reduced and, if the plutonium is "burned" at an international fuel cycle center, the ratio of nationally to internationally generated nuclear power would be about ten in a light-water cycle.[2,6] An additional nonproliferation advantage is that the produced U^{233} is accompanied by U^{232}, which leads to the emission of energetic gamma rays in its decay and thus to greater difficulty in handling spent fuel. This same feature of course increases occupational hazards in reprocessing and recycling.

This concept of denaturing might be carried to the extreme of eliminating entirely transfers of fissile material once a reactor is in operation.[3] An example of such a reactor is the *molten-salt breeder*, a technology which received considerable support in earlier US programs before being eliminated in favor of plutonium breeders. If the molten-salt reactor can be engineered to have a breeding ratio of unity, then once it is loaded with fissile material, its annual fuel makeup would consist only of thorium. Fission products would be removed by a small on-line reprocessing plant which would not have the capability for removing fissile material. Fissile material, after its initial loading, would not be accessible without shutting down the reactor. While molten-salt reactors would have lower breeding gain, they make more efficient use of fissile resources during a period of growth, because they have a smaller initial fissile inventory (about 2500 kg versus 6000–7500 kg for a comparable liquid-metal breeder).[2] A plutonium breeder would have to operate for more than twenty years to breed enough fissile material to overcome this initial inventory disadvantage. *Gaseous-core reactors*, with similar advantages, have also been proposed; these alternatives to the liquid-metal fast breeder all require, and all deserve, further technical development.

The relative nonproliferation advantages of these alternative cycles require further study; it is not difficult to foresee possible technical and political problems. For example, the relatively large isotopic mass difference between U^{233} and U^{238}, used in some denatured fuel cycles, may make separation of weapons material possible with even crude centrifuges (though this would still involve a certain national dedication and time). However, the greatest difficulty in reducing proliferation hazards through the use of alternate fuel cycles may be in achieving the necessary international cooperation.

Except for once-through cycles, all advanced cycles appear to require some form of international organization. For example, the denatured U^{233}–thorium cycle would require international fuel centers (or continued dependence of non-weapons states on supplier countries already possessing weapons); the molten-salt cycle would require a source of initial fuel and perhaps international su-

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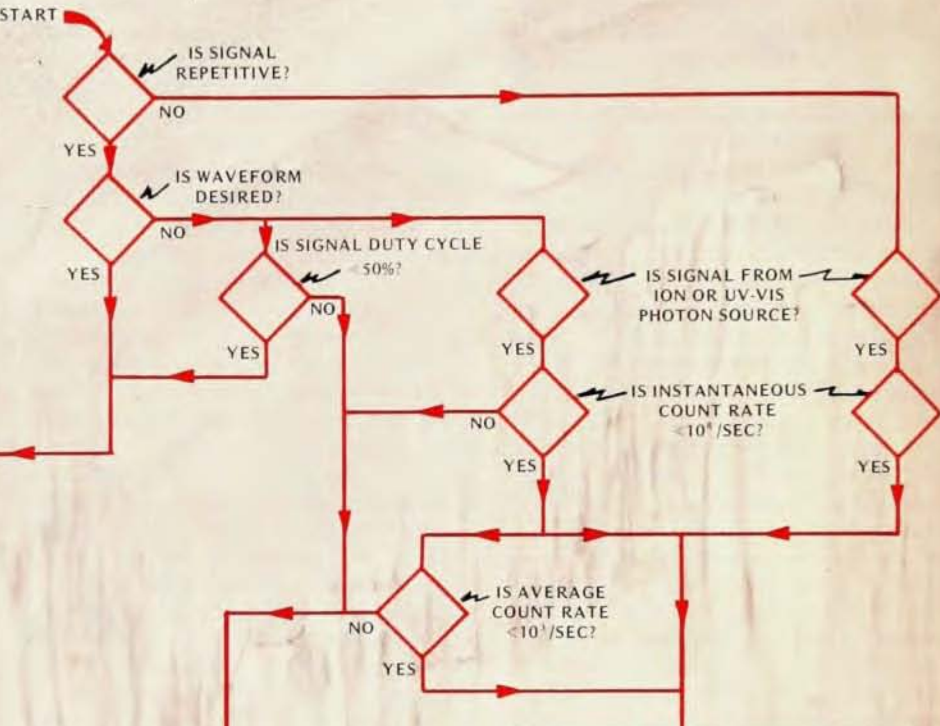

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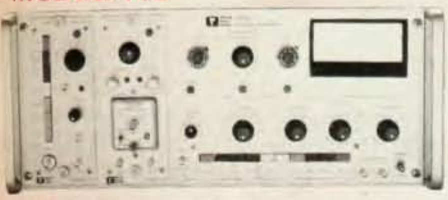

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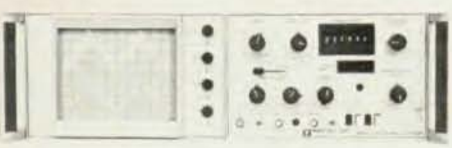

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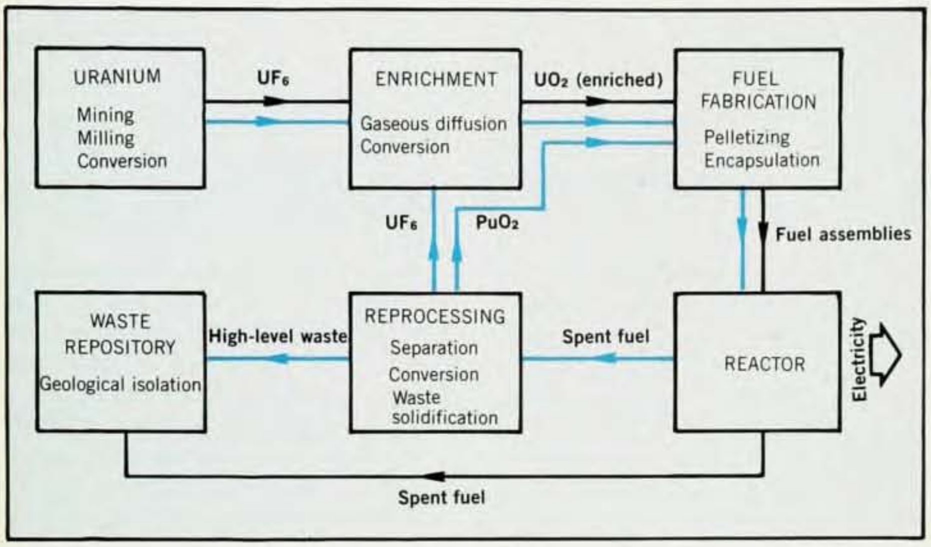
pervision of initial fueling and subsequent reactor operation. However, it is possible that the institutional problems associated with alternative cycles have solutions that are more easily achieved than those required by plutonium fuels.

Choices and prospects

Basic technological choices in nuclear power have a strong bearing on proliferation risks. In the past, choices have been made on the basis of economic and technical factors, with a conviction that technical and political measures would be found that would allow new technologies to be accommodated safely. The recognition that proliferation concerns should enter explicitly into technology choice represents a new phase in the 30-year effort to establish distinctions between peaceful and non-peaceful uses of the atom.



An idealized representation of the fuel cycle for a light-water reactor, without recycling (black lines) and with recycling (colored lines). Flow charts for other cycles are similar.

Table 2. Lifetime uranium commitments for several thermal-reactor options

Options	Uranium commitment (short tons)
Light-water reactors	
U, no recycling	6410
U, with U recycling	5280
U and Pu recycling	4340
U + Th, U recycling	3650
U + Th, spectral shift	<3000
Heavy-water reactors	
Natural U, no recycling	5263
U (1% U^{235}), no recycling*	3800
Natural U, Pu recycling	2861
Pu–Th, U recycling	2210
High-temperature gas-cooled reactors	
U^{235}–Th, U recycling	2970
Pu–Th, U and Pu recycling	4990

The data are for a 1000-MW(e) reactor operating at 80% capacity factor for 30 years. Enrichment is at 0.2% tails assay for those cycles utilizing enriched uranium. From APS report, reference 2. The capacity factors achieved so far have been considerably lower than 80%; for average capacity factors in the 60% to 75% range, the uranium commitments can be approximated by scaling down the results shown above.

* This result has been obtained by adjusting for different capacity factor the result of Y. I. Chang *et al* (Argonne) and assumes a fuel burnup of 16 MWD(th)/kg.

Bringing nonproliferation concerns into the process of technology choice is made difficult by the narrowing of technical options that has already occurred in response to uncertainties in uranium supply and projections of high nuclear growth rates. The result in most supplier countries has been a decision to pursue early commercialization of plutonium recycling and plutonium breeders. In developing and less-developed countries, the primary locus of many proliferation concerns, energy problems are severe, but the ability of advanced fuel cycles to alleviate these problems will be much lower or much delayed, resulting in less real need to commit to such cycles. Nevertheless, the expectation that plutonium breeders would soon provide significant energy benefits has led some of these countries to attach high value to acquisition of pilot reprocessing plants and plutonium stockpiles. Because of the long lead times associated with nuclear power development, proliferation problems can precede, by decades, the actual utilization of the technology.

There is as yet no worldwide agreement on whether it is possible or desirable to reshape the nature and pace of evolution of nuclear power technology.

In the US, research and development efforts are shifting away from early commercial demonstration of the plutonium breeder towards broadened consideration of fuel cycle options. The Carter Administration has deferred plutonium recovery from spent light-water reactor fuel, citing the negative effects a US commitment would have on decisions being made in other countries and on US efforts to restrain the pace of plutonium commitments, and pointing to threefold reductions in the nuclear growth projections that motivated early commitments to plutonium.

The long-term international impact of these program shifts is unclear. Several advanced countries have indicated their intentions to proceed with reprocessing and plutonium-breeder development. This has suggested to some that the US is pursuing an isolationist course, which will deny it the opportunity to help in devising technical and political solutions to the proliferation problems posed by what is seen as an inevitable use of plutonium fuels.

In contrast, the proponents of the Administration strategy argue that the real source of US leverage is through considerations other than commercial rivalry, such as fuel assurance or security arrangements. They also observe that proliferation risks arise in the great majority of countries without plutonium committments, countries where US restraint may at least prevent accelerating commitments before plutonium fuel cycles have been shown necessary or controllable by international institutions.

Those arguing for a broader domestic research and development program also point out that the US, with extensive uranium deposits and research capabilities, is in a unique position to develop nuclear power alternatives. If worldwide uranium supplies prove much greater than the conservative assumptions used in planning nuclear-power programs abroad, the US may have advanced other reactor concepts to the point where they can be made available at a net advantage in economics as well as nonproliferation. The possibility that new technologies may become available is also seen as possibly restraining near-term commitments to plutonium, especially in less developed countries.

How this discussion will be resolved, and what the consequences will be for nuclear power and for nonproliferation, are yet uncertain. In the longer term—beyond the year 2000—there are reasons for pessimism: Increasing technological sophistication and technology transfers, especially isotope-separation techniques, may undermine technological approaches to avoiding proliferation. The relative importance of political and institutional approaches will thereby be increased. In the nearer term, it is possible to be more optimistic about opportunities to deal with proliferation risks and perhaps avoid largely those associated with nuclear power. Over the next decade, nonproliferation goals would be served by deferrals of plutonium commitments, improved worldwide fuel assurance and examination of alternative fuel cycles from a nonproliferation perspective.

Reactor fuel cycles

The source of energy in the nuclear fuel cycle is the neturon-induced fission of uranium or plutonium in a nuclear power reactor, each fission releasing about 200 MeV of energy and several neutrons. The useful fissile isotopes are U^{235}, U^{233} and Pu^{239}, although only U^{235} is available in Nature (approximately 0.7% of natural uranium is U^{235}, the rest being U^{238}). The other fissile isotopes can be bred by neutron capture on fertile isotopes:

$$U^{238} \xrightarrow{(n,\gamma)} U^{239} \xrightarrow[23.5\ m]{\beta^-} Np^{239} \xrightarrow[2.4\ d]{\beta^-} Pu^{239}$$

$$Th^{232} \xrightarrow{(n,\gamma)} Th^{233} \xrightarrow[22\ m]{\beta^-} Pa^{233} \xrightarrow[27\ d]{\beta^-} U^{233}$$

These reactions offer a considerable resource extension because the fertile isoptes U^{238} and Th^{232} are fairly common in Nature and because a sufficiently large number of neutrons are given off in fission to breed new fuel as well as to sustain the chain reaction. In a breeder reactor more fissile material is produced than is consumed.

The average fission-neutron energy is about 1 MeV, but the cross section for fission is orders of magnitude larger at lower energy. Reactors therefore currently operate on a thermal-neutron spectrum, meaning that the fission neutrons are moderated by collision with a light element. This is either hydrogen (in light-water reactors) or deuterium (in heavy-water reactors).

The number of neutrons emitted per neutron capture by thermally fissile isotopes varies from 2.1 to 2.3 with thermal neutrons, but is as high as 3.0 for Pu^{239} with fast (1-MeV) neutrons. The U^{233}–Th cycle offers the greatest potential conversion ratio for thermal reactors, while U^{235}–Pu cycle in a fast-neutron spectrum offers the greatest potential resource efficiency. This is one reason why most research and development has emphasized development of the plutonium-fueled fast-breeder reactor. However, that reactors can be designed to operate on virtually any combination of fissile, fertile and moderating materials.

Although the power reactor is clearly at the heart of the fuel cycle, a considerable number of supporting facilities are needed. A flow sheet for the light-water-reactor fuel cycle, with and without plutonium recycling, is shown in the figure opposite; the other fuel cycles are not qualitatively different.

The uranium ore is mined, milled, converted to gaseous UF_6 and fed to an isotopic enrichment facility. Here the isotopic fraction of thermally fissile U^{235} is raised from 0.7% to around 3% by gaseous diffusion through porous barriers. This technology is very capital- and energy-intensive and future enrichment capacity will likely rely on the gas-centrifuge process. The enriched gas is converted to solid UO_2, which is fed to the fuel-fabrication plant.

When spent fuel is discharged from a reactor, it is intensely radioactive because of fission products. A light-water reactor with capacity 1000 MW (electric) discharges about thirty tons of spent fuel per year, containing about 250 kg of plutonium (about 70% fissile) and a comparable amount of U^{235}. With or without recycling of this fissile material, it is envisioned that these fission products will be sent to a Federal nuclear waste repository for long-term geological isolation from the biosphere. A pilot-plant repository is scheduled for operation in 1985. The spent fuel is now being stored in cooling ponds.

With plutonium recycling, the spent fuel would be sent to a reprocessing facility. There, the plutonium and uranium would be separated chemically from the fission products and, if desired, from each other. The plutonium would then be converted into solid PuO_2 and sent to a mixed-oxide-fuel fabrication plant for combination with enriched uranium and incorporation into fuel assemblies. The uranium would be converted into UF_6 and recycled. The stream of high-level waste would contain the radioactive fission products (plus residual amounts of plutonium and other actinides). After cooling, these would be incorporated into a solid matrix (for example, of borosilicate glass) and transported to the waste repository. The recycled plutonium and uranium would improve resource utilization by reducing uranium requirements.

We stress that this fuel cycle is just one of many options, albeit the one that has received the most research and development. The flow sheet for any of these cycles is generically the same as the above, except that some employ thorium as a fertile material and that some do not require uranium enrichment.

Different thermal reactor options may lead to different breeder choices; for example, a U^{233}–Th cycle might supply initial fueling for molten-salt breeders (thermal breeders operating on the thorium cycle), in the way the U–Pu light-water cycle was expected to fuel liquid-metal plutonium breeders.

Goals for the eighties

It is vital to future nonproliferation efforts that the time available prior to widespread plutonium utilization be used well. We can list three primary technical goals for the next decade:

- a comprehensive worldwide assessment of uranium and thorium resources, using advanced exploratory techniques and supported by governments at levels commensurate with the long-term value of this information;
- immediate efforts to improve efficiency of resource utilization in once-through reactor fuel cycles, and
- advancement of various breeders (including the plutonium breeder) and advanced-converter reactors to the point where the merits of each, including nonproliferation advantages, can be assessed on a common ground by governments and industry.

It is too early now, and the basis for choices too narrow, to make decisions that would put major limitations on our future abilities for dealing with long-term energy supply and proliferation problems. For at least a few years, the costs of developing better information are not high compared to the potential benefits.

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