NUCLEAR POWER AND NUCLEAR WEAPONS PROLIFERATION

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THE ISSUES

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 questions of supply assurance have become issues of intense international concern. Unlike other energy sources, however, nuclear power raises another class of security issues through its potential for contributing to the acquisition of nuclear weapons by national or even by subnational groups. Nations must therefore consider the extent to which energy supply and nuclear weapons nonproliferation goals can be made compatible.

This issue of compatibility is not raised with equal urgency by all forms of nuclear technology, nor are the political and technical opportunities for international control the same for different nuclear fuel cycles. At present, the commercial nuclear power industry in the United States and in most other countries operates on low-enriched uranium. (See the appendix for a brief description of fuel cycle technology.) The reactor fuel consists of uranium enriched to about 3% in the fissile isotope U-235 (natural uranium contains 0.7% U-235, the rest being U-238) and cannot be used in a nuclear weapon without further isotopic enrichment. Commercial enrichment through gaseous diffusion requires both advanced technology and enormous resource commitments and is still restricted to a few supplier countries. New technologies, such as centrifuges or eventually laser enrichment, may change this situation and thus pose a serious challenge to nonproliferation strategies, but this challenge is unlikely to arise for at least a decade.

The more immediate and serious concern with regard to the proliferation implications of nuclear fuel cycle activities comes from the long-anticipated world-wide 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 recovered, can be used to extend naturally available nuclear fuels. This extension is relatively modest with present thermal reactors (a resource savings of about 25%). However, plutonium-utilization in breeder reactors can yield a resource extension of about a factor of fifty. Uncertainty over the magnitude of natural uranium reserves, with some estimates implying a uranium shortage in this century, have stimulated vigorous development of plutonium alternatives. Further, the possibility for diminishing reliance upon imports is particularly attractive to those countries lacking secure access to uranium and nonnuclear fuels. Commitments to plutonium are imminent but not yet widespread. Commercial scale reprocessing of spent fuel and recycle of plutonium is only now beginning[1] with a plant operating in France and plants, either near operation or planned, in Japan, the United Kingdom, and other European countries. In the United States, a large plant at Barnwell, South Carolina is partially completed, although its completion and operation have been deferred indefinitely. Plutonium breeders are just beginning to emerge from the research and development stage and commercially significant breeder deployments could not occur at least until near the end of this century.

The imminence of large scale commercial utilization of plutonium has stimulated concern about the attendant increase in proliferation risks. These risks arise not only in the eventual presence in the fuel cycle of large quantities of separated plutonium suitable for use in nuclear weapons but also in the anticipatory investments many countries may make in plutonium technology or stockpiles. An important distinction with regard to proliferation implications must be drawn between future developments in enrichment technology and future widespread plutonium utilization. In the latter case, the basic technology is known already and pilot scale separation plants, built to acquire experience for future commercial operation, are immediate sources of weapons material.

In the United States, these concerns have led to intensive reexamination of the technical, economic, and political assumptions underlying both domestic and international nuclear policies. This evaluation was first signalled officially by President Ford in his statement of October, 1976 which said, in part:

> I have concluded that the reprocessing and recycling of plutonium should not proceed unless there is sound reason to conclude that the world community can effectively overcome the associated risks of proliferation. I believe that avoidance of proliferation must take precedence over economic interests[2].

President Carter has deferred indefinitely domestic plutonium utilization and called for world-wide reexamination of nuclear power issues. This reexamination, with participation by most supplier countries, will take place over the next two years. In the United States, several extensive studies of nuclear power issues[3] have been completed within the last year.

The world-wide debate over the relative benefits and costs of plutonium utilization involves a complex interrelated set of political, technical, and economic questions on which there is as yet little agreement. The primary benefits of plutonium utilization were alluded to above: an extension of fissile resources and a measure of independence from external suppliers. Furthermore, it is widely believed that reprocessing and recycle are important steps in reducing risks in the management and disposal of nuclear wastes. The values ascribed to these benefits by the many governments participating in the debate vary considerably. The countervailing set of issues involves the magnitude of associated proliferation risks and the extent to which they might be reduced. Some have argued that there are no essential connections between nuclear power development and weapons since many countries could now achieve weapons capabilities through dedicated facilities. However, this argument ignores the potential scale of a commercially fed plutonium weapons program and, more importantly, the different political dynamics involved: in pursuing plutonium fuel cycles, countries drift closer, in time and technical capability, to weapons without having to make and sustain the long-range national political decisions involved in a dedicated program. The latent proliferation inherent in accessibility to large amounts of weapons material can have destabilizing political ramifications even without actual weapons construction. These problems are considerably less acute in the low enriched uranium fuel cycles, since large resource and technological commitments, and several years time, are needed to acquire weapons material. These technical barriers are reinforced by the provisions of the Nonproliferation Treaty, which has been ratified by 102 nations, and by international safeguards systems administered by the International Atomic Energy Agency. An important question regarding future plutonium fuel cycles is whether practical international safeguards measures can reduce proliferation risks to similarly acceptable levels. These issues, involving both technical and political factors, will be discussed in greater detail in the sections following.

NUCLEAR FUEL CYCLES AND RESOURCE UTILIZATION

Fissile materials which 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 an explosive (see table 1). However, the ease with which such material can be recovered for weapons use varies greatly with fuel cycle. The central difference between uranium and plutonium fuels in this regard is that the former can be isotopically denatured while the latter cannot. That is, the thermally fissile isotopes U-235 and U-233, when diluted with U-238 to isotopic content less than 15 to 20%, cannot be used in a nuclear weapon since sufficiently rapid supercritical assembly becomes impractical. Consequently, isotopic enrichment is necessary. Many nations have the capability for enriching uranium on a small scale, but these dedicated facilities would be quite inefficient, could yield only small output, and would have an appreciable chance of detection during the years required to complete a program.

On the other hand, the critical mass for plutonium of any isotopic composition is quite small (see table 2). This does not mean that an efficient, high-yield explosive is manufactured easily with plutonium. In particular, Pu-240 creates a substantial neutron background because of spontaneous fission and, since the chain reaction is initiated with neutrons, sophisticated design is needed to avoid pre-detonation (i.e., premature initiation of the chain reaction). However, this problem is certainly surmountable and, in any case, the yield from a nuclear "fizzle" can still be extremely large compared with that from conventional explosives. Therefore, comparatively simple chemical separation of plutonium from reactor fuel, the technology for which is described in great detail in the open literature, leads to weapons material. Of course, the plutonium-bearing spent fuel from the present uranium fuel cycle is intensely radioactive from fission-product activity and thus requires remote handling facilities. With plutonium recycle, the fission products are removed during reprocessing so that weapons grade material becomes directly accessible.

Given the possibility of increased security risks arising from adoption of plutonium fuel cycles, it is important to review critically the benefits which might attend their introduction. The first is resource extension. With self-generated recycle, LWR lifetime uranium requirements are reduced by about 32%[4]. For an expanding reactor system, however, recycle has a smaller net impact, perhaps 20 to 25% in the United States over the next decades. Furthermore, even this assumes that all plutonium is recycled to LWR's, whereas a considerable fraction of it would be set aside for breeder start-up if optimal plutonium utilization were to be achieved. With uranium prices near those now prevailing, recycle would increase or decrease the busbar cost of nuclear generated electricity by at most a few percent. Estimates are uncertain within this range because of uncertainties in the costs of uranium, reprocessing, mixed oxide fuel fabrication, waste management, safeguards, and plant financing.

In the United States, known uranium resources are adequate to permit deferral of recycle for perhaps two decades. Present ERDA estimates of high-grade U.S. uranium resources, recoverable at forward costs $30/lb or less, total 3.8 million tonnes. This includes ERDA's categories of reserves plus probable, possible and speculative resources; about half the total is in the reserves plus probable resources categories. There is controversy about what the ERDA figures mean in terms of future reserves and uranium production rates. One group regards the estimate as an upper bound which will be difficult to reach, particularly if uncertainties inhibit development of mining production capabilities. Others point to the fact that the ERDA estimates are based on industry data from limited geological environments, developed when uranium prices were much lower than they are today, concluding that these estimates are likely to be a lower bound on supplies ultimately available. The 3.8 million tonnes at $30 forward cost estimated by ERDA would be adequate to fuel about 600 GW(e) of LWR capacity for thirty years. Recent estimates of domestic nuclear power growth envision deployment of about 300 MW(e) capacity by the year 2000. There is little data on which to base estimates of resources available at higher costs. Increased exploration and reserve definition, stimulated by higher uranium prices and government assessment efforts (the National Uranium Resource Evaluation program) should lead soon to much better knowledge, and a major expansion in proven reserves is quite likely. Also, it is important to note that deferral of recycle, with interim storage of spent fuel, leads to only modest loss of fissile resources.[5] It is clear that resource considerations alone do not motivate recycling in the near future.

While the LWR recycle decision is not now strongly constrained by resource availability, research and development and demonstration strategies for new fuel cycle technologies depend more critically on long-range projections about resources and nuclear growth rates. Diminishing resources, reflected in very high uranium prices, and expanding LWR deployments may eventually require introduction of much more efficient converter or breeder reactors if nuclear power is to continue to contribute to energy supply. If plutonium breeders are used, spent fuel reprocessing would have to begin some years earlier to provide both start-up fuel and experience in commercial scale reprocessing. Until recently, projections of high nuclear growth rates (900 to 1200 GW(e) capacity by 2000) were seen as necessitating breeder introduction in the early 1990's. Changes in growth projections and proliferation concerns have led to reconsideration of R, D & D strategies.

The extent to which other countries may defer commitments to plutonium is unclear. The uranium fuel issue abroad is less one of resource magnitude and more one of accessibility to supply over the long periods implied by a commitment to nuclear power. Indeed, Western Europe and Japan appear to have compelling energy supply reasons for pursuing such cycles: heavy dependence on imported energy and lack of extensive indigenous uranium deposits make even marginal fuel assurance gains attractive. Fuel assurance is also of concern in the less developed countries, despite their relatively small nuclear power programs. The LDC's generally operate at the margin of energy supply systems, a precarious situation when economic development is strongly dependent on growth in energy supply. In balancing fuel assurance against the security risks of plutonium, such nations may weight the former consideration more heavily. Yet, it is an unavoidable fact that the domestic and regional instabilities faced by some LDC's make them a primary locus of proliferation risks.

The more urgent energy supply needs of other countries do not necessarily imply a need to commit now to plutonium fuels. As in the U.S., plutonium recycle in current generation reactors abroad would only marginally reduce dependence: low-enriched uranium is the primary fuel and still must be acquired through world market or other mechanisms. Consequently, improvements in the efficiency of uranium utilization and improved assurance of long-term supplies of uranium may relieve some of the pressure for near-term plutonium utilization. For LDC's, the contribution of plutonium technology to reduction of the external dependencies implied by rapidly growing energy needs would be extremely small for at least several decades. Early commitments to plutonium technology, such as pilot scale reprocessing plants, may be reduced by efforts on the part of supplier countries to improve fuel assurance and to provide alternative energy technologies better suited to LDC energy needs. Without these efforts, attempts by industrialized countries to constrain LDC technology and fuel choices will be seen as discriminatory and as further institutionalization of the inequalities inherent in the Nonproliferation Treaty[6].

Interim non-plutonium options can help remove the basis for charges of discrimination while promoting efficient resource utilization. Resource extensions comparable to those achievable with LWR plutonium recycle are possible with modification of current fuel cycle operation or with alternate thermal reactor fuel cycles (see table 3). For example, without recycle, the natural uranium fueled, heavy water moderated reactor now operated in Canada (the CANDU) is significantly more resource efficient than the LWR. Other options are offered by the thorium cycle, in which U-233 is bred and recycled. As an example, modification of LWR's for spectral shift operation[7] with thorium fueling can reduce ore requiements by more than a factor of two. These gains can be important in providing more time to develop effective internationally agreed upon non-proliferation strategies prior to a commitment to widespread plutonium utilization. It must be realized that the thorium cycles, which require recycle of U-233, are not an immediate option since reprocessing of spent uranium/thorium fuels still requires extensive engineering development and pilot-scale experience. However, these cycles are not needed immediately since the pressure on uranium resources, and a consequent need for more efficient reactors, could not become serious until near the end of the century, if production and distributional problems can be solved. Alternate thermal reactor fuel cycles offer the opportunity for deferring the transition to a breeder economy.

The final element in the debate over the necessity for early reprocessing and recycle is the problem posed by nuclear wastes. Eventually, nuclear wastes must be sequestered from the biosphere, most likely in stable geological formations, such as salt beds. Since plutonium is a major source of radioactivity in wastes after about 500 years, some have concluded that intergenerational risks would be reduced by removal and subsequent utilization. It has also been argued that the conditioning received by waste after reprocessing, embedding it in borosilicate glass, for example, decreases the risk of leaching if the integrity of geological isolation is breached. Recent studies, however, suggest that the technical advantages gained are at best small. While at most a factor of ten reduction in long-term actinide activity can be accomplished by plutonium recycle[8], there may be a compensating increased risk to current generations. Moreover, the efficacy of geologic isolation, in a favorable groundwater regime, is such that risks from failure are very small and virtually independent of wasteform.[4] Finally, preliminary studies suggest that the leachability of spent fuel may in fact be lower than that of glass.[9] On technical grounds there thus appears to be little imperative to begin reprocessing as part of a waste management and disposal program. Like the other problems discussed here, however, how wastes are treated is not entirely a technical problem: political issues have come to be involved. In some countries, earlier convictions about waste treatment have been made part of the law, with plans or even contracts for reprocessing required for reactor licensing. Because there is considerable public concern about nuclear wastes, some believe that reconsideration of present laws could increase political opposition to nuclear power generally.

STRATEGIES FOR CONTROL

Strategies for limiting proliferation risks must take into account the nature of the risks involved and the technical and political opportunities for dealing with them presented by particular fuel cycles. Risks are associated with the possibility of subnational theft of fissile material and with the possibility that nations will misuse fuel cycle facilities or divert materials. These problems are quite different in nature and deserve separate consideration. In the next decade, fuel cycle choices are limited to low-enriched uranium and plutonium recycle fuels, and the relative merits of these choices in providing opportunities for control should be compared. In the longer term, alternate fuel cycles based upon thorium as the fertile material may have value in restricting access to weapons materials, as discussed below.

Safeguards against Subnational Theft

The amount of plutonium needed for a nuclear explosive (several kilograms) is very small compared to that present in a plutonium-fueled nuclear economy. Consequently, extremely effective security measures are needed over the lifetime of the industry. Safeguards include physical security and technical measures intended to make theft or diversion difficult, increase the chance of detection if diversion occurs, and make weapons fabrication more difficult and time consuming. Physical security measures during transportation might include armed guards, massive transportation casks and special communications systems; at reprocessing and mixed oxide fuel fabrication plants surveillance and tightly controlled access to process streams and storage areas would be used. 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. These measures are specifically suited to the control of nuclear materials. Accountability approaches involve neutron and high-resolution gamma ray measurements intended to monitor accurately the flow of fissile material through fuel cycle facilities. Under development are systems in which the measuring devices are coupled to a central computer for real-time analysis. Accurate accountability is most easily achieved at the same fuel cycle points at which the fissile material is most accessible for diversion. Such schemes may be very important in maintaining effective security over the lifetime of a fuel cycle facility.

Fuel form modification could involve preirradiating or spiking with radioactive isotopes (to make theft and subsuquent handling more dangerous), incorporation of intense neutron sources (complicating weapons design), or dilution of plutonium with uranium (to force chemical processing of the material). None of these measures provides a "technical fix" against misuse of fissile material; they can, however, gain time for recovery forces following theft. Of course, these measures must be consistent with safe normal operation of the fuel cycle and, consequently, the comparatively simple dilution approach is particularly attractive. Dilution can be accomplished by mixing following processing or by adjusting the reprocessing chemistry so that plutonium and uranium are coprocessed and thus never completely separated. The latter approach is especially desirable for safeguards.

Physical security and technical safeguards 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 in reprocessing plant operations and somewhat complicates mixed oxide fuel fabrication. Political and social costs are also involved, the most frequently mentioned of which is the impact of security measures on civil rights of nuclear workers, or on the public which might become involved in efforts to recover stolen material.

The economic costs involved in implementing physical security are certain to be small compared to the overall cost of nuclear generated electricity. However, the cost/benefit calculation is made difficult by the unquantifiable nature of the subnational threat and by the difficulty of agreeing on what constitutes an "acceptable" level of risk. This problem is particularly important in the international context since not all countries will evaluate and weigh risks in the same way. The feasibility of a universal safeguards system has a significant bearing even on domestic terrorist risks, with the general level of risk depending on the lowest levels of security achieved worldwide. If these questions can be resolved, it is plausible that the subnational threat can be satisfactorily met through a combination of physical security and technical safeguards. In the United States, this determination awaits the establishment of safeguards performance criteria by the Nuclear Regulatory Commission.

Strategies for International Control

The safeguards applied to subnational diversion are largely ineffective in preventing governmental diversion of fissile material or misuse of nationally controlled fuel cycle facilities. This is because governments exercise control over the fissile material and have considerable resources at their disposal for overcoming technical barriers. Consequently, safeguards against national proliferation involve very important political components and operate primarily through the threat of detection and subsequent international response. To be effective, three elements are essential: an appreciable chance of detection, suitable international political mechanisms, and time for these actions to occur prior to completion or use of weapons. An appreciable chance of detection is not only the basis for the deterrence effect of safeguards but also provides a signal initiating international actions deterring final realization of weapons status or dealing with its security consequences. Such actions would include efforts to relieve security threats motivating acquisition and sanctions or other measures increasing the costs of completing a weapons program. Since these actions can be of great value before weapons are acquired but are of limited utility afterward, adequate time is vital to their success. Plutonium fuel cycles magnify the problems of detectability and response time, because of the large amounts of potential weapons material involved and its relatively quick accessibility. If utilization of plutonium fuels makes it possible for countries to achieve a rapid transition from non-weapons to weapons status, it would undermine a primary source of international leverage on the national proliferation problem.

With the present low-enriched uranium fuel cycle, safeguards center primarily upon bilateral supplier/customer agreements and upon inspection by the International Atomic Energy Agency. However, the primary guarantors of the safeguards agreements are the substantial technical and political commitments and time needed to acquire large amounts of weapons grade material from this fuel cycle and the concomitant appreciable chance of detection. By contrast, the large amount of plutonium separated in a reprocessing plant would require considerably more intrusive, and politically sensitive, international inspection to be effective. Automated internationally-controlled accountability systems offer some hope but are unlikely to achieve sufficient accuracy to alleviate uncertainties about systematic small-scale diversion at the reprocessing plant or subsequently prior to recycle in a reactor. Such accounting is complicated by, among other things, the great variety of physical and chemical forms in which plutonium appears in process and waste streams.

Acquisition of plutonium or highly enriched uranium is often stated[10,11] to be the most difficult step in constructing a nuclear explosive. Consequently, the time between abrogation of safeguards agreements and weapons availability is potentially shortened to as little as a few days if ancillary technical development occurs before diversion. Steps such as bomb design and tests of ordinary explosive detonators can be performed without violating international agreements and without appreciable fear of detection. Preparation not entailing major potential political liabilities may become part of the contingency planning of even relatively secure nations. This trend toward latent proliferation greatly lowers the threshold to weapons acquisition and presents a major nonproliferation challenge.

Internationalization of fuel cycle activities has been proposed and 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. This has the effect of greatly reducing the opportunities for one nation to divert fissile material. However, there are formidable political realities to be confronted in establishing such centers. For example, one of the strong motivations for desiring nuclear weapons is likely to be regional rivalry and conflict; but, it is precisely this regional insecurity that makes the establishment of a fuel cycle center difficult. In addition, it is conceivable that internationalization would even contribute to proliferation by providing mechanisms for accelerated transfer of sensitive technologies to individual states.

Denatured Thorium Fuel Cycles

The thorium fuel cycle offers an alternative to the U/Pu fuel cycle with both substantial resource extension and possibly enhanced opportunity for international safeguards control. For safeguards purposes, the fuel cycle could be operated so that strategic quantities of weapons grade material appear separate from fission products only in multinationally operated fuel cycle centers. National light water reactors could be fueled with U-233/U-235, diluted with U-238 to less than 15 to 20% of the uranium, plus thorium as the fertile isotope. The spent fuel would be returned to an international fuel cycle center for reprocessing. Such a fuel cycle, discussed first by Feiveson and Taylor[12] and also in the APS report[4], is more resource efficient than the LWR uranium fuel cycle, even with plutonium recycle. Plutonium production is reduced by a factor of five to seven with respect to current LWR production. In reprocessing, the plutonium could either be left with the fission products and treated as waste or be separated. In the latter case, the plutonium could be consumed in a reactor located at the international site; if all the plutonium is to be used, the ratio of off-site to on-site nuclear power (i.e., nationally versus internationally controlled) is restricted to about ten to fifteen [4,12]. Nevertheless, this is sufficiently large to allow for flexibility in establishing the needed international agreements and to confine weapons grade material to a comparatively small number of international sites.

The safeguards advantage of this cycle is that the fresh fuel provides weapons material only after further isotopic enrichment. An additional deterrent to diversion or theft of spent fuel, especially by subnational groups, is that the fuel loading can be such that the concentration of plutonium is so low that a large amount of radioactive spent fuel must be reprocessed. However, there are also serious problems to be found in implementing this denatured fuel cycle: political difficulties stand in the way of internationalization; technical development is still needed for commercial scale reprocessing of spent thorium fuels; a potential safeguards problem is generated by the somewhat simpler enrichment of U-233/U-238 fuel (because of the larger mass difference). However, the safeguards advantages of a denatured fuel cycle may make it easier to overcome the political difficulties of internationalization than would be the case with plutonium fuels. Therefore, the thorium cycle could represent an attractive longer-range option.

The effectiveness of any restriction on the rate or direction of international nuclear growth must be judged within the general context of alternate national routes to weapons capability. All fuel cycle operations are technically within the means of many non-weapons states. A uranium enrichment program, free of the constraints of large throughout and competitive economics, could use comparatively simple means to support a very small weapons program. The design and operating characteristics of natural uranium fueled reactors are in the open literature and could be constructed and used as plutonium production reactors[13]. A simple chemical separation plant, designed for small batches and low burn-up fuel, could be constructed using freely available technology. In fact, these dedicated routes would yield higher quality weapons material than would be obtained by diversion of commercially produced plutonium. Nevertheless, as stressed above, plutonium fuel cycles aggravate the problem of latent proliferation. The dedicated routes are time-consuming, lead to small weapons programs in most cases, and are more likely to be detected. A nation committing itself to such a program must confront the risks involved, including the possibility of strong international response throughout the duration of the program. Such restraints, coupled with a genuine international concern about nuclear proliferation, appear to have played an important role in slowing proliferation; latent proliferation is likely to weaken them. These factors must be weighed along with those of energy supply assurance in considering future nuclear development.

CHOICES AND PROSPECTS

Nuclear power is but one of many factors in the complex international problem of proliferation. Increasing technical sophistication, due only in part to the spread of nuclear power, will enable more countries to acquire nuclear weapons if desired. Decisions to acquire weapons will be made on the basis of perceptions of security and prestige, but will also recognize the potential political and economic costs involved during and after the weapons acquisition process. Nonproliferation strategies must therefore include measures which reduce incentives or create disincentives to weapons acquisition. Examples include efforts to relieve security threats or to increase political and economic costs of weapons decisions. Present nuclear power programs, involving use of low-enriched uranium and very limited availability of enrichment capabilities, have only an indirect coupling to weapons programs since dedicated routes would usually be preferable, involving no greater time and lower political costs and resulting in superior weapons materials.

The evolution of nuclear power technology, particularly the spread of new enrichment technology or the use of plutonium fuels, may, however, increase the relative importance of nuclear power considerations in the proliferation problem. The difficulties of devising measures to reduce the proliferation hazards of plutonium have been discussed above. Strategies for dealing with proliferation aspects of future nuclear power developments must recognize the diverse energy supply problems of particular countries, uncertainties about uranium resources and their accessibility, and the varying status of commitments to new nuclear technologies, such as reprocessing and plutonium breeders. Proliferation concerns arising in connection with the LDCs are especially troublesome since energy security and political security are both fragile and, in the case of plutonium fuel cycles, highly interdependent. To relieve both kinds of security concerns in ways which do not increase proliferation hazards requires use of nuclear fuel cycles or alternative energy sources which allow separation of these issues.

The most important issue in considering strategies to deal with proliferation is whether the world has choices and the time in which to make them. Many believe that there is not time - that the momentum of programs to begin reprocessing and to commit to plutonium for recycle and breeders is too great and too closely tied to insecurity of energy supply, to the need to resolve waste management problems, and to the need to sustain public confidence in nuclear power. This belief, which is particularly strong in France, Germany, and Japan, has as its consequence a need to get on with the job of designing technical and political fixes to the problems associated with the long-anticipated evolution of nuclear power.

The analysis above suggests that this view may be too rigid and that the desired technical and political fixes are as yet of limited efficacy. Since plutonium is not essential on resource grounds until at least near the end of the century, the rate at which commitments to plutonium cycles are made could certainly be slowed, perhaps to a pace more amenable to political accomodation. Alternative fuel cycles which offer better political and technical opportunities for control also have a good chance of being available before resources put major constraints on nuclear growth. These conclusions are especially relevant in the LDCs, where the benefit of plutonium fuel cycles could only be achieved much later than in the developed countries. Eventually, of course, the evolution of technology - for example, the spread of centrifuges or the development of laser isotope separation technology - will change the nature of the proliferation problem. At that time we will have only political measures on which to rely. The immediate problem, however, involves the anticipatory investments in pilot reprocessing plants and plutonium stockpiles which might be made in the next few years.

By this mechanism, the latent proliferation which would accompany a full-scale plutonium economy occurs even earlier.

What is needed is the opportunity to shape and slow the evolutionary process. Technology choices in the past were usually made solely on economic and technical grounds, a process which favored technologies easily derived from military programs. This process, carried on in weapons states on behalf of all potential users, did not necessarily result in choices which offer the best opportunities for dealing with the problems of nuclear weapons proliferation in the contemporary world. Slowing the rate at which commitments to plutonium are realized, especially in pilot plants during the next decade, may be essential to dealing with the latent proliferation problem. A world in which only a few countries are considering such commitments is undoubtedly more stable than one in which dozen of countries make the transition to incipient weapons status simulteneously.

Decisions made in the developed countries will affect, but not determine, the ways in which nuclear power develops elsewhere. Deferral of domestic commitments to plutonium fuels puts supplier states in a stronger position to argue against early commitments in other countries. Reexamination of nuclear development plans also serves to raise questions and create pressures for realistic open analysis of the cost/benefit tradeoffs involved in particular fuel cycle choices. While such examples may not induce all countries to defer commitments to plutonium fuels, the converse is probably true: commitments in the advanced countries would ensure earlier and more widespread use in the less-developed countries. It should be realized that there are potential costs involved in this course if deferral of plutonium puts greater pressure on uranium supplies and if plutonium commitments are made without safeguards developed in supplier country fuel cycle programs. Efforts to improve fuel assurance, particularly in the LDCs, and to attach safeguards to all fuel cycle operations, must be considered essential to nonproliferation efforts. If these efforts are made, the balance of risks favors the present course of cautious reappraisal. The gains ultimately achieved may be limited but they are very important. For at least a few years, and perhaps for much longer, the costs of restraint and caution are not high.

Appendix

REACTOR FUEL CYCLES

A generic flow sheet for the light water reactor fuel cycle, with and without plutonium recycle, is shown in Figure 1. The first requirement is, of course, a source of uranium. The 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% (the value found in natural uranium) to about 3%; the remainder of the uranium is U-238, which is not fissionable by thermal neutrons. The enriched gas is converted to solid UO_2, which is fed to the fuel fabrication plant. Eventually, gaseous diffusion may be replaced by other enrichment technologies, such as centrifuge or laser enrichment.

The heart of the fuel cycle is the power reactor, where neutron-induced nuclear fission generates heat and subsequently electricity. Commercial reactors currently operate on a thermal neutron spectrum, meaning that the neutrons given off in fission are moderated (i.e., slowed down) so that advantage can be taken of the much larger fission cross section at low energies. Most commercial reactors use ordinary water H_2O as the moderator and are termed light water reactors (LWR). An LWR with capacity 1000 MW(electric) discharges about thirty tonnes of intensely radioactive spent fuel per year. The heat and radioactivity in the spent fuel are due primarily to the fission products and, with or without recycle, 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-scale repository is scheduled for operation in 1985. Prior to this, and in the absence of recycle, the spent fuel is being stored in cooling ponds.

The thermally fissile material employed in a reactor can be U-235, U-233, or Pu-239. Although the latter two are not available in nature, they can be bred by neutron capture on fertile isotopes:

$$^{238}U \xrightarrow{(n,\gamma)} {}^{239}U \xrightarrow{\beta^-} {}^{239}N_p \xrightarrow{\beta^-} {}^{239}Pu$$

$$^{232}Th \xrightarrow{(n,\gamma)} {}^{233}Th \xrightarrow{\beta^-} {}^{233}Pa \xrightarrow{\beta^-} {}^{233}U$$

These breeding reactions offer a considerable resource extension because the fertile isotopes U-238 and Th-232 are fairly common and because a sufficiently large number of neutrons are given off in fission to breed new fuel as well as sustain the chain reaction. Plutonium is bred in operation of an LWR fueled with low-enriched uranium. Some of this bred material is subsequently fissioned, contributing significantly to power production; the remainder exits in the spent fuel. For typical LWR operating conditions, the spent fuel contains about 250 kg of plutonium (approximately 70% fissile) and a comparable amount of U-235.

With plutonium recycle, the spent fuel would be sent to a reprocessing facility. There, the plutonium and uranium would be separated chemically from the fission products and 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 low-enriched uranium and incorporation into fuel assemblies. The uranium could be converted into UF_6 and recycled. The high level waste stream would contain the radioactive fission products (plus residual amounts of plutonium and other actinides). After cooling, these would be incorporated into a solid matrix (e.g., borosilicate glass) and transported to the waste repository. The recycled plutonium and uranium would improve resource utilization by reducing uranium ore requirements.

Numerous other fuel cycles are feasible. Thermal reactors can be operated on virtually all combinations of moderator (water, deuterium (heavy water), and graphite) and fuel (any of the three fissile isotopes in combination with fertile uranium or thorium). The fuel cycles are not qualitatively different from that described above, except that, in some cases, the reactor is operated on natural uranium fuel (e.g., the Canadian, heavy water moderated CANDU reactor). However, resource efficiency is quite different for the various fuel cycles (see table 3 in the text).

Breeder reactors which utilize fast (i.e., unmoderated) neutrons can also operate on virtually all combinations of fissile and fertile materials, although there is variation in the amount of excess fissile material bred. Recycle is obviously mandatory in breeder fuel cycles. The most efficient cycle, and the choice almost exclusively being developed, is that based on plutonium. However, all breeder cycles result in greatly increased efficiency of use of fissile resources when compared with fuel cycles not involving recycle.

FOOTNOTES AND REFERENCES

1.) Nuclear Fuel Services operated a small plant in West Valley, New York during 1966 to 1971. However they processed only 600 tonnes of spent fuel, and about two-thirds of this came from the AEC's Hanford N-reactor.

2.) Office of the White House Press Secretary, October 28, 1976.

3.) The Nuclear Energy Policy Study (Nuclear Power: Issues and Choices, Ballinger Publishing Co., Cambridge, 1977) sponsored by the Ford Foundation and administered by the MITRE Corporation, provides a comprehensive look at the many technological, economic, and political issues involved in the nuclear power debate. The technical issues underlying policy decisions, including those concerned with waste management and alternative fuel cycles, have been examined by an American Physical Society study group,("Report to the American Physical Society by the Study Group on Nuclear Fuel Cycles and Waste Management," to be published in Reviews of Modern Physics). The Congressional Office of Technology Assessment has issued a report focusing upon the safeguards and nonproliferation issues (Nuclear Proliferation and Safeguards, Library of Congress Catalog No. 77-600024).

4.) The APS report (see reference 3).

5.) Approximately 16% of the thermally fissile plutonium in spent fuel is Pu-241, which has a 15-year half-life.

6.) Signatories to the Nonproliferation Treaty who do not already have nuclear weapons agree not to develop such weapons. In return, the weapons states agree to make available technology for peaceful applications of nuclear energy.

7.) For spectral shift operation, the reactor coolant system is modified to include both H_2O and D_2O, with the D_2O/H_2O ratio decreasing through a fuel burn cycle.

8.) Multiple recycle leads to increased amounts of long-lived transplutonic actinides in the spent fuel.

9.) Battelle Northwest Laboratories BNWL-20-57 (1976); and paper "Leaching of Irradiated LWR Fuel Pellets in Dionized Water, Sea Brine, and Typical Ground Water," Y.B. Katayama, J.E. Mendel, presented November 29, 1977 at American Nuclear Society Meeting (San Francisco).

10.) M. Willrich and T.B.Taylor, "Nuclear Theft: Risks and Safeguards", (Ballinger Publishing Co., Cambridge, 1974).

11.) The OTA report (see Reference 3).

12.) H.A. Feiveson and T.B. Taylor, Bulletin of Atomic Scientists (1976) 14.

13.) J.R. Lamarsh, Library of Congress, Congressional Research Service QC170 Gen. (1976).

Table 1

Critical Mass of Uranium as a Function

of Uranium-235 Enrichment*

Enrichment (% U-235)	Critical Mass (kg.)
100	15
80	21
60	37
40	75
20	250 (approx.)
10	1300 (approx.)

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*Uranium spheres with density 19 g/cm.^{3} in a 15 cm. natural uranium neutron reflector. From T.B. Taylor, "Nuclear Safeguards," Annual Review of Nuclear Science, 25 (1975).

Table 2

Critical Mass of Plutonium as a Function

of Plutonium-239 Content*

Volume Fraction of Pu-240 plus Pu-242	Critical Mass (kg.)
0	4.4
10	5.0
20	5.6
30	6.7
40	7.8
50	9.6

*Alpha-phase plutonium spheres in thick uranium neutron reflector. From T.B. Taylor, "Nuclear Safeguards," Annual Review of Nuclear Science, 25 (1975).

Table 3

Lifetime Uranium Commitments for

Several Thermal Reactor Options*

Option	Uranium Commitment (short tons)
LWR	
U, no recycle	6410
U, with U recycle	5280
U and Pu recycle	4340
U + Th, U recycle	3650
U + Th, spectral shift	<3000
HWR	
Nat. U, no recycle	5263
Nat. U, Pu recycle	2861
Pu-Th, U recycle	2210
HTGR	
U-235-Th, U recycle	2970
Pu-Th, U and Pu recycle	4990

*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 3).

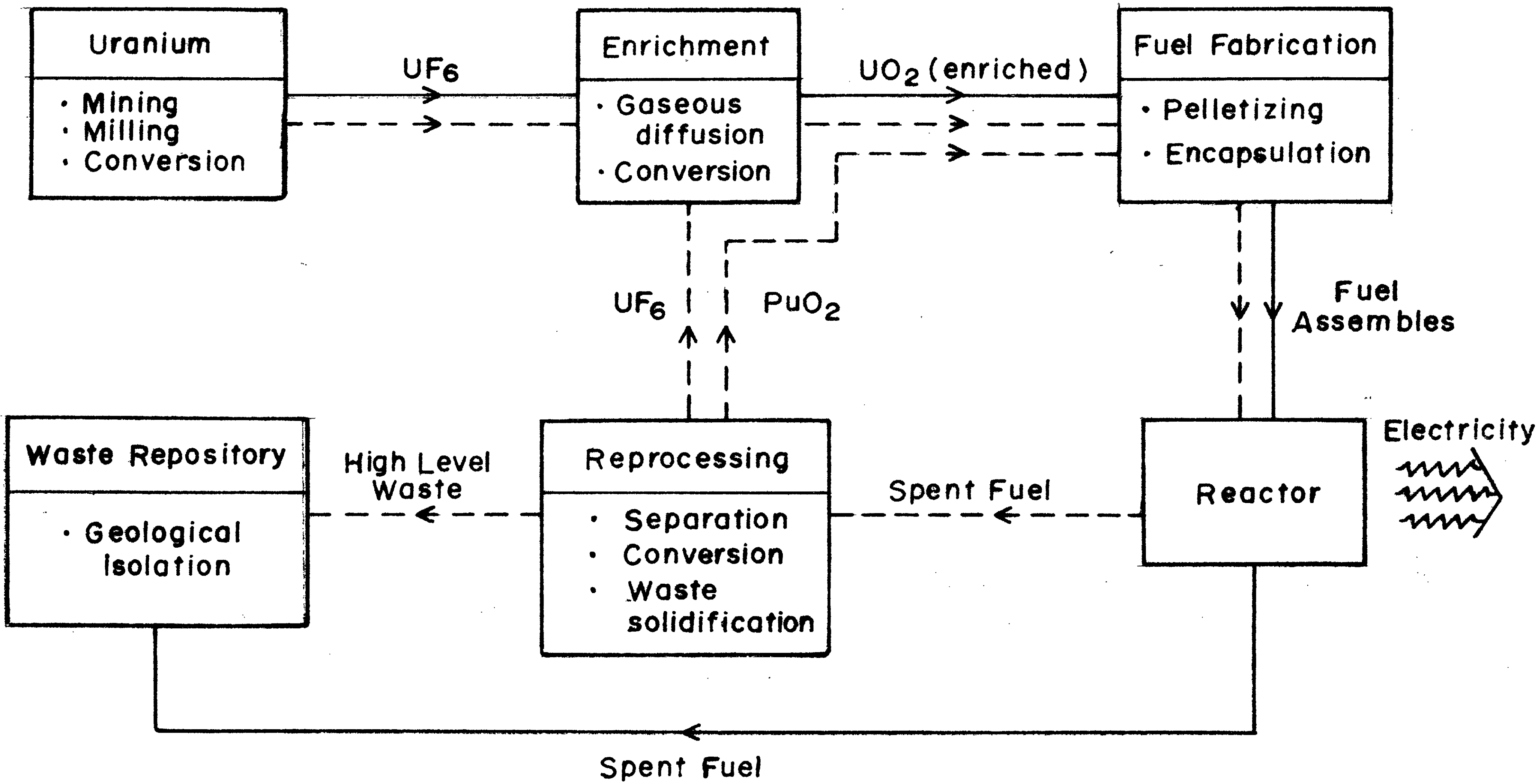

Fig. 1. Idealized representation of the light water reactor fuel cycle, without recycle (solid lines) and with recycle (dashed lines)