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Nuclear Power: A Balanced Approach

A mix of breeders and advanced converters can best meet the needs of the future.

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The outlook of the nuclear industry has changed substantially over the last few years. While our national energy policy necessarily involves a major and increasing role for nuclear systems at least well into the next century and beyond, the nature of this involvement is clearly a matter of widespread debate. A strategy is proposed here to ease the evolution of nuclear power into our energy economy by providing an array of options against future uncertainties and a bridge from today's technologies to those needed for a continuing major role for nuclear power. It calls for a symbiotic combination of breeders and advanced converters, based on both the uranium and thorium cycles, in an approach responsive to some of the major concerns expressed on the issues of weapons proliferation, uranium resource conservation, and economics.

Summary. A proposed technological approach to meeting recognized nuclear power needs is a symbiotic combination of breeders and advanced converter reactors. Breeders, situated in secured areas, would be fueled with and self-sufficient in plutonium. The excess fuel produced in the breeder would be uranium-233, sufficient in quantity to supply several advanced converters located near load centers. This approach is suggested as a balanced way to meet important criteria applicable to the continued development of nuclear power.

The principal casualty of the nuclear debate in the past year or two has been the base technological strategy for nuclear development that evolved within government and industry over a quarter of a century. That strategy called for deploying light-water reactors (LWR's) as rapidly as utilities could economically use them; developing commercial reprocessing and fuel fabrication facilities; recycling plutonium in LWR's; and giving high priority to the development of liquid metal fast breeder reactors (LMFBR's) so that they would penetrate the LWR market in the late 1980's and 1990's and rapidly take it over.

Criteria for a New Strategy

The most frequent criticisms of this base strategy in today's nuclear power debate fall into four general categories:

1) The early recycling of plutonium in existing LWR's and later in LMFBR's would bring plutonium into commerce before adequate safeguards could be erected against an increased risk of nuclear weapons proliferation (*1–4*).

2) The urgency that prompted the government to expedite the development of the LMFBR is greatly reduced, a consequence largely of reduced nuclear power growth forecasts (*1*, *3*).

3) The capital cost of the LMFBR appears to be trending toward levels much higher than those for the LWR (*5*).

4) The obstacles encountered in siting conventional nuclear power plants do not augur well for the availability of sites for a whole new generation of LMFBR's.

The suggested change in technological approach to one of a symbiotic combination of breeders and advanced converters is not a new idea, but it is an idea whose time may have come in response to these criticisms (*4*, *6*, *7*). It should meet in a balanced way the criteria of many who are concerned over the future of the nuclear energy option. There are four of these criteria that seem particularly pertinent in the consideration of any new strategy.

The first criterion is that proliferation risks should be limited. Proliferation problems cannot be solved by the choice of a fuel cycle, but selection of appropriate fuel cycles and their means of deployment can make easier the development of both safeguard procedures and institutional arrangements that reduce the risk of proliferation. Moreover, any approach should have the flexibility to adapt to changes in policies on safeguards and proliferation (*8*).

The second criterion has to do with uranium resource requirements, that is, U_3O_8 needs, and refers to the limits on both cumulative and yearly uranium production that must be considered in any nuclear power deployment strategy.

The third criterion is that the technological approach should be consistent with, and indeed promote, a stable nuclear industry for the long-term future, with appropriate regard for environmental and siting issues.

The final criterion concerns economics and simply refers to the fact that the implementation of any long-range strategy will be affected, perhaps decisively, by economics.

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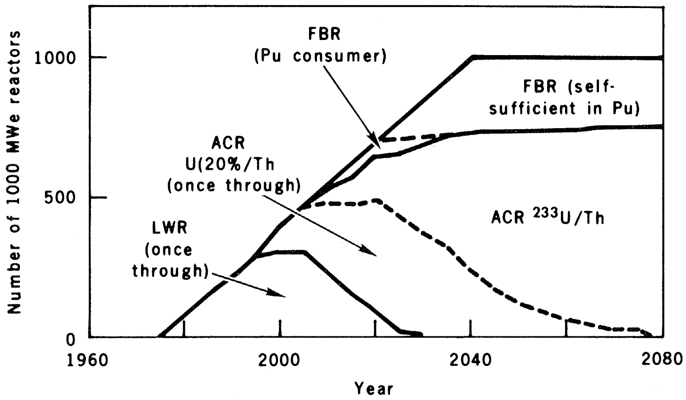

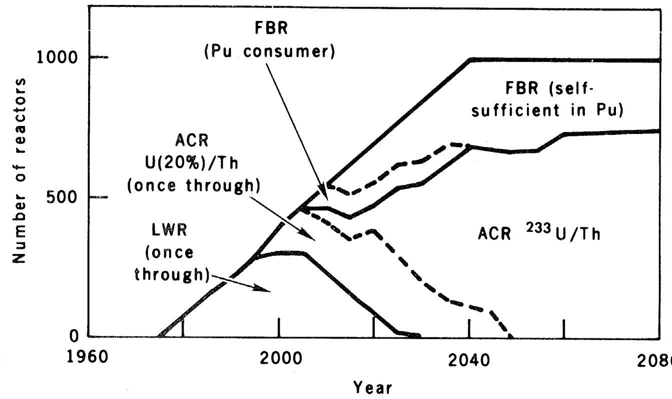

Fig. 1 (left). Gradual deployment of FBR's. Requirements for U_3O_8 would be about 3.3 million tons.

Fig. 2 (right). Early emphasis on FBR's. Requirements for U_3O_8 would be about 2.2 million tons.

Any view of the future must recognize that most reactors currently operating and under construction in the United States are LWR's. Any strategy or policy guiding future developments must include the continued improvement of these reactors, in performance, economics, and resource utilization. By not emphasizing this aspect herein we do not mean to imply that it is unimportant. Rather, we want to focus attention on some new ideas that could well involve improved LWR's and LWR fuel cycles as key elements.

The New Strategy

The ultimate goal of the new strategy (*9*) is to reach a condition where one breeder fuel factory supports several (perhaps three to four) advanced converters (*10*). The breeder in this proposed symbiotic approach has three essential functions: (i) it produces excess fuel that is used in the advanced converter reactors (ACR's); (ii) it produces enough fuel to meet its own needs; and (iii) it produces electrical power.

While the fuel in the core of the fast breeder would be plutonium, to sustain its operation, the fuel produced for use in thermal spectrum ACR's would be ^{233}U bred from thorium in the blanket of the breeder. The breeder fuel factories, because of proliferation concerns, could be situated in secured facilities, the number of which should be kept to a minimum.

In contrast, ACR's, fueled nearly entirely with ^{233}U and thorium, would be sited outside of secured areas and near load centers. With ^{233}U as the fuel, the conversion ratio of the ACR can be very high (more than 0.9). This leads in turn to low yearly fuel requirements for the ACR and to a high ratio (3 or 4 to 1) of ACR's to breeders. The use of the thorium cycle and the resulting ^{233}U in the ACR's is essential here because it is only with ^{233}U in a thermal neutron spectrum that conversion ratios of 0.9 or more can be obtained. In contrast, if only the plutonium-uranium cycle were deployed for breeders and, say, LWR's, it would require about one fast breeder to supply the makeup requirements of one thermal reactor.

The intense radioactivity associated with the ^{233}U, a consequence of the ^{232}U formed by nuclear processes as the ^{233}U is formed, would not eliminate proliferation concerns, but it would help significantly. Uranium-233 must be handled remotely behind heavy shielding. The dose at a distance 1 meter from a fresh fuel element containing recycling ^{233}U is about 1 rem per hour. The radiation dose at 1 meter from an 8-kilogram sphere of reactor grade ^{233}U that is 3 months old is 3 to 4 rem per hour, increasing for 1-year-old material to 10 to 20 rem per hour (*11*). To put this in perspective, the average lethal dose is about 500 rem.

As a further nonproliferation measure, it should be noted that ^{233}U could be mixed with ^{238}U (that is, denatured) to an extent that would make it even more unsuitable for weapons application. This might be desirable at least until safeguarding procedures are developed. Such denaturing could be accomplished either in situ or at the reprocessing plant.

The CIVEX reprocessing concept (*12*) for the recycling of plutonium and uranium fuels in breeders also could be used with the thorium cycle if desired. In this concept, to discourage diversion of the fuels, selected fission products would be left in the recovered fissile materials—in the plutonium-uranium mixture in the case of the plutonium-uranium cycle or in the ^{233}U in the case of the thorium cycle. The resulting dose rate 1 meter from a several kilogram quantity of material would be several hundred rem per hour.

For national weapons programs, however, the radioactivity associated with the ^{233}U may be nearly as effective in discouraging diversion as the much higher activity resulting from the fission products in the CIVEX process. National programs will not be ad hoc or temporary efforts but well-planned longer-range efforts, and the health and safety of the technologists involved will require nearly as much care and shielding with ^{233}U as with contaminated material in the CIVEX process. In fact, to the extent that isotope separation is more difficult than chemical purification, the radioactivity associated with ^{233}U may be a greater discouragement to proliferation than a contaminated fuel mixture.

The Transition

Our present nuclear economy is based on LWR's operating on low enrichment–uranium fuel, and these will continue to be the major nuclear power producers for at least the next 20 to 30 years. The objective of the new strategy, however, is an economy of breeders and ACR's where the latter could be high-temperature gas-cooled reactors (HTGR's), heavy water reactors (HWR's), or advanced LWR's operating on the ^{233}U-Th cycle. There are any number of ways of getting from here to there. Two that appear to bracket many of the possibilities can be described through the use of a simple but reasonable model.

In this model, the nuclear economy is assumed to be about 400 gigawatt-electric by the year 2000, increasing thereafter at a rate of 15 GWe per year until the year 2040. The 1000 GWe reached at that time is then held constant. The indicated growth rate and the capacity in the year 2000 are consistent with recent projections by the Department of Energy (*13*). The 1000-GWe limit is not an important part of the model, but it facilitates the comparison of strategies.

The actual future is certain to be different from the details of this model, but the date and rate of deployment of both advanced converters and breeders can be adjusted to fit actual conditions as they evolve. Flexibility is a prerequisite for any strategy.

The two modeled alternatives are shown in Figs. 1 and 2 (*14*). These two options differ in the rate at which breeders are introduced. The option shown in Fig. 1 assumes a gradual deployment of breeder fuel factories beginning about the year 2000; the second, in Fig. 2, assumes a much faster deployment of breeders. The advantage of a gradual rate is that it reduces the need for reprocessing facilities and helps in the establishment of secure energy centers. The advantage of a faster rate is that it reduces cumulative U_3O_8 needs.

In both modeled alternatives, LWR's are assumed to operate on the once-through cycle. The discharged fuel being stored for eventual reprocessing represents a fuel resource for the later breeder fuel factories. Advanced converter reactors, also operating on the once-through cycle, are introduced in the 1990's. However, the preferred fuel here is thorium and 20 percent enriched uranium. Use of thorium in these early ACR's is important because it starts to build the ^{233}U resource for later high performance ratio ACR's.

About the year 2000, breeder reactors are deployed, reaching a total in the gradual breeder introduction option of 60 by the year 2020. These initial breeder fuel factories are net consumers of plutonium; the cores are plutonium-uranium fueled, but all of the blankets are thorium. The large amount of ^{233}U produced is used in the inventories of high conversion ratio ACR's.

The use of ^{233}U as the fuel for ACR's begins about the year 2005. Also, when appropriate, ^{233}U will replace the U (20 percent)-Th fuel in already operating ACR's.

As the ^{233}U inventory needs for the advanced converters are met, the breeder fuel factories (net consumers of plutonium and prolific producers of ^{233}U) are gradually converted to be self-sufficient in plutonium. This conversion begins about the year 2020.

The "flow" of nuclear fuel thus goes as follows. The plutonium needed to fuel the breeder fuel factories comes from two sources: (i) discharged LWR fuel and (ii) discharged U (20 percent)-Th fuel from the early ACR's. The ^{233}U for the high conversion ratio ACR's also comes from two sources: (i) discharged U (20 percent)-Th fuel from the early advanced converters and (ii) the blankets of the breeder fuel factories.

The gradual breeder deployment option requires 3.3 million tons of U_3O_8 to achieve and maintain an inexhaustible nuclear energy production of 1000 GWe, whereas the faster deployment strategy requires only 2.2 million tons.

Several other variations in this basic strategy have been studied, primarily to determine the sensitivity of U_3O_8 requirements to the timing of certain elements of the strategy. The conversion of advanced converters from the U (20 percent)-Th once-through cycle to a ^{233}U inventory with recycling could be delayed 20 years at a cost of about 0.4 million tons of U_3O_8. If the use of highly enriched ^{233}U in advanced converters were never possible, necessitating the use of denatured ^{233}U instead, there would be two penalties with reference to the gradual breeder deployment option: (i) cumulative U_3O_8 requirements would increase by about 0.7 million tons; and (ii) the ratio of breeder fuel factories to advanced converters would decrease to about 1:1, complicating the establishment of secure energy centers.

Common to all of the strategies studied, however, is that advanced converter reactors operating on the U (20 percent)-Th cycle should be deployed in the 1990's, and also that breeder fuel factories be demonstrated during the 1990's so that the option for their deployment would be assured by the year 2000. Preferably, there would be more than one breeder demonstrated, given the importance of these fuel factories.

Evaluation of New Strategy with Respect to Criteria

How does this new approach measure up against the four criteria mentioned earlier? With respect to limiting the risk of proliferation, the long-range situation is improved over the old strategy because there are fewer breeders operating on the uranium-plutonium cycle, there are more ACR's operating on the ^{233}U-Th cycle, and the fuel in commerce is reactor grade ^{233}U (*15*, *16*). But the transition strategy also is responsive to proliferation concerns, specifically:

1) The gradual introduction of breeder reactors and ancillary reprocessing plants makes easier the establishment of secure sites for nuclear facilities. By the year 2020, the nation will need about 60 breeder fuel factories, a number that might be accommodated on 10 to 20 secure sites. Reprocessing requirements would also be minimized to, perhaps, less than one for each secure site.

2) The ACR's first introduced are operated in the once-through mode. Conversion to higher performance plants, for example, with conversion ratios greater than 0.9, occurs later as ^{233}U becomes available. Depending on policies and concerns at the time, the recycling of ^{233}U in ACR's either could be postponed or could be in the form of denatured ^{233}U for a few years.

With respect to U_3O_8 requirements, the cumulative uranium demands in the two alternatives are well within most estimates of the available resources, which range from a low of about 2 million tons to a high of well over 4 million tons (*17*). If further exploration indicates that U_3O_8 estimates on the low side are more accurate, emphasis on establishing breeders at an early date may be necessary for a continuing strong nuclear enterprise. Hence, the basic strategy provides a hedge against the possibility that U_3O_8 resources are minimal.

The peak yearly U_3O_8 requirements for either of the two approaches are about 60,000 tons, within the projected capacity of the industry (*18*-*20*).

The new strategy preserves the long-term nuclear option. There is flexibility to increase the total nuclear capacity (to a value greater than 1000 GWe) by either the use of additional U_3O_8 resources or a temporary increase in the ratio of breeders to ACR's. The siting flexibility inherent in a mix of fast and thermal reactors also augurs well for the long term.

Finally, with respect to economics, if breeder capital costs remain high relative to those for thermal reactors, a possibility that cannot be discounted given continuing experience both in the United States and in Europe, then a nuclear demand met with a combination of breeder fuel factories and ACR's, rather than primarily with breeder power producers, will be economically more attractive to the utility industry and will provide energy at a lower cost to the consumer.

Fuel Cycle Considerations

The additional mining and milling capacity that is required for the thorium cycle is modest. The thorium inventory needed to fuel an advanced converter is about 50 tons, compared to about 400 tons of U_3O_8 for a standard LWR. For the proposed new strategy, which requires a peak yearly production of about 60,000 tons of U_3O_8, a production of only about 2000 tons of thorium per year would be necessary; that is, the thorium mining and milling industry would need to grow to only a small fraction of the size of the uranium industry.

The reprocessing requirements for the new strategy also are gradual and modest. If it is assumed that one reprocessing plant can handle the output of about 50 GWe of generating capacity—that is, a plant approximately the size of Barnwell—one plant to reprocess LWR fuel to get the plutonium inventory for the fast breeder demonstration plants would need to go into operation in the 1980's. Another plant would be required in the year 2000, followed by one more in 2010, with perhaps a total of four light-water fuel-reprocessing plants in operation by the year 2020. One thorium-reprocessing plant to obtain the ^{233}U fuel for the high-performance ACR's would be required in the year 2000, with another two plants coming on-line in the following decade. With the first breeder fuel factory deployment beginning in the year 2000, one additional breeder reprocessing plant would be required by the year 2010 and another two in the following decade. Compared to the investment in the power plants themselves and in mining and milling facilities, the investment in reprocessing facilities appears to be quite small.

Finally, the thorium cycle is the key to the flexibility inherent in the ACR-fast breeder reactor symbiosis, where this ratio can be adjusted to meet varying conditions in uranium supply and nuclear power economics.

Much of the technology for the recycling of thorium fuels is already well in hand, a consequence of a major technology program centered at Oak Ridge National Laboratory over many years.

International Implications

The applicability of the proposed strategy to the needs of other countries will, of course, vary from country to country, but substantial interest in the thorium cycle, the key to the new strategy, is already evident in the national programs of several countries. The flexibility of the new strategy is considerable, and it would seem that the potential is there for broad international application.

One of the key problems, of course, is the location of secure sites for breeder fuel factories and reprocessing facilities. Nations that already possess nuclear weapons are obvious candidates for such secure areas, but the establishment of regional centers with regional management, control, and security, and with International Atomic Energy Agency (IAEA) safeguards and inspection regulations, appears to be a practical and promising goal.

Given the existence of secure areas for nuclear facilities, advanced converters could be sited near load centers under national control and operation, but also with appropriate IAEA safeguards and inspection regulations. The fuel would be ^{233}U, denatured if necessary.

The problems involved with the internationalization of the fuel cycle are likely to be formidable, however. More insight into this subject will be gained over the next 2 years as the NASAP and INFCE programs go forward (*21*).

References and Notes

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21. The Nuclear Alternative System Assessment Program (NASAP) is a governmental initiative to evaluate various nuclear fuel cycles with respect to proliferation resistance and commercialization potential, and to study ways to reduce proliferation risk. The International Nuclear Fuel Cycle Evaluation (INFCE) program is an ongoing effort on the part of many nations to study the interaction of civilian nuclear programs and weapons proliferation and to suggest ways of reducing the risk of proliferation (*1*).