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Nuclear Power and Energy Security: A Revised Strategy for Japan

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SUMMARY

During the period of nuclear power's rapid growth, shared assumptions regarding uranium resources and technological capabilities led the majority of industrial nations to remarkably similar strategies for nuclear power deployment. These common assumptions motivated the choice, more than 40 years ago, of the Light Water Reactor (LWR) as the near-term power reactor, to be followed, as soon as possible, by the introduction and deployment of the Fast Breeder Reactor (FBR). The FBR, which uses much less uranium than an LWR of the same capacity, was a crucial part of the strategy because uranium was then believed to be a scarce resource. This strategy, based on the LWR producing the startup fuel for the FBR, implicitly included spent fuel reprocessing, plutonium recycle, and disposal of separated wastes in geologic repositories. Nations with limited indigenous energy reserves, most notably France and Japan, made particularly strong commitments to this strategy.

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With the passage of time, it has become clear that the technology associated with this strategy has serious problems. More significant, however, has been the gradual realization that uranium is a widely available resource, with large, inexpensive terrestrial reserves and with essentially inexhaustible marine reserves recoverable at prices which would have minimal impact on the busbar cost of nuclear electricity.

It was the predicted near-term (i.e., before 1990) acute shortage of uranium that was the main justification for the choice of LWR/FBR technology. That choice would not have been made otherwise, because other nuclear reactor designs, and other fuel cycles, were known to have substantial advantages with respect to safety, economy, proliferation resistance, and energy security. The LWR is costly, necessarily complex in its dependence on the strategy of "defense-in-depth" to minimize the risk of serious accidents, and relatively unforgiving of error. Development of the particular FBR design that was chosen to meet the predicted near-term shortage, the liquid metal (sodium) cooled FBR (LMFBR), encountered numerous unanticipated technological problems and is unable to meet many of its original design goals. The fuel reprocessing and recycling required for the LWR/FBR fuel cycle, is complex and uneconomical in comparison to the LWR once-through fuel cycle, creates multiple waste streams, and significantly increases the risk of misuse of the fuel cycle for the acquisition of nuclear weapons.[1]

As a result of these factors, the United States and other countries which have made a major investment in developing and deploying nuclear power have abandoned the LWR/FBR route to energy security, and are de-emphasizing the LWR as a future energy source. Japan has been reluctant to follow this route because of its near total dependence on imported fuels. Even if energy security were not an issue, Japan's considerable investment in nuclear power argues against a sudden change in its long range plans to rely on nuclear power for a significant fraction of its electrical power needs. However, there is a simple and economic multistage strategy that can guarantee the continued contribution of the existing LWR-based nuclear sector to Japan's energy security in the near and intermediate terms, while enhancing long-term energy security and economic gain by adding reactor types which have the potential for easier local deployment and a significant export market. This strategy includes research and development of reactors which could provide high temperature process heat, thus allowing nuclear power to play a greater role in assuring energy security and supply.

The proposed near-to-intermediate-term strategy is based on the stockpiling of natural or low enriched (reactor grade) uranium in sufficient quantity to ensure continued operation of the installed LWR reactor fleet on a once through cycle for a period of at least several decades. The expense of such an "insurance stockpile" could be largely, if not completely, offset by savings made available by redirection of spending from the breeder to research and development of reactors operating on once-through cycles with enhanced safety, reduced long-lived waste generation, higher efficiency, and process heat potential.

The need to develop, and eventually to deploy, new reactor designs does not arise only from concerns regarding uranium supply. Even with assured fuel availability, the "monocultural" LWR fleet is itself a source of insecurity because of the impossibility of demonstrating by actual test that safety, based on defense-in-depth, can prevent catastrophic failures. Generic flaws, either real or suspected, can result in reduced availability or even shut-down of the entire fleet. This possibility has become an increasingly important impediment to growth of the nuclear sector. Thus, there is strong incentive to develop fundamentally different reactor types that could be deployed without arousing such safety concerns. Such reactors could better take advantage of the technological progress in reactor design and power conversion systems that has occurred since the choice of LWR technology nearly 50 years ago. The Modular Gas-cooled Reactor with gas turbine power conversion, for example, offers enhanced safety, process heat capability and, the potential of a very profitable export market.[2] A diversified reactor fleet would enhance energy security whether or not external uranium supplies were available.

Continued reliance on nuclear power for electricity and process heat in the long term would be assured by the availability of seawater-derived uranium in large quantities at a cost that would have only marginal effects on the price of nuclear energy production. Although studies on "mining" uranium from seawater were initiated more than 30 years ago in England,[3] it is the R&D carried out in Japan which has established the technical and economic feasibility of the technology.[4] The guaranteed availability of uranium at reasonably low and predictable prices facilitates development of reactors optimized for such features as demonstrable safety, proliferation resistance, export capability, and process heat production, without the compromises required by recycle and breeding.

INTRODUCTION

The paradigmatic LWR/FBR nuclear power system was conceived in the United States over 50 years ago, and soon achieved "Official Technology" status, with resulting strong government support, preferential access to capital, and the capture of path dependent advantages.[5] The LWR/FBR approach rapidly became dominant, aided by its Official Technology status and by aggressive state-subsidized marketing. The LWR very quickly began to make significant contributions to power production in the U.S. and other industrialized countries and the FBR became the singular focus of development efforts.

However, after very rapid expansion in the 1970–1990 time period, nuclear power's rapid growth has slowed significantly; in some countries, installed nuclear capacity has actually started to shrink. Overall, the nuclear share of global electricity production, 17% in 1996, has begun to decline, and the current economic crisis in Asia does not bode well for growth in a region where rapid growth had been anticipated.[6] The other components of the LWR/FBR paradigm, the breeder and plutonium recycle, have not fared even as well. The U.S. and Germany have abandoned their breeder programs. The French government has recently announced that the 1200 MWe Superphenix breeder reactor will be dismantled, while the Japanese demonstration breeder, Monju, remains shut down more than two years after a loss-of-sodium accident. The situation is almost as bleak for recycle of plutonium as Mixed-Oxide (MOX) fuel in LWRs; existing contracts are being honored but MOX fuel is not popular with reactor operators or the public.

Nuclear power, in its present incarnation, has not lived up to its great promise. The fundamental question is whether such failure is inherent and unavoidable or if, perhaps, other technological embodiments of nuclear power systems can satisfy society's economic and political requirements. There is good reason to suspect that other implementations of nuclear power technology might allow nuclear power to play a greater role in energy supply and energy security. The current LWR/LMFBR scheme is, after all, just one of many fundamentally different ways to exploit nuclear energy. It was chosen in response to the political and military conditions existing circa 1950, on the basis of contemporary assumptions regarding uranium and fossil fuel availability, the anticipated growth rate of nuclear power, and the predicted costs associated with both the FBR and the associated reprocessing technology. At the time, it was believed that uranium was in critically short supply and that fossil fuel prices would soon rise sharply, that nuclear power would become the dominant energy source, and that the costs of the FBR and its fuel cycle would actually be less than that of the LWR. All of these assumptions have proven to be false. Now, a better understanding of the actual situation along with improvements in technological capability make it possible to develop a clearer idea of nuclear power's proper role in energy supply, and to develop technological embodiments that optimize the desired characteristics.

HISTORY—RUNUP TO CURRENT STATUS

Nuclear reactors were developed in secrecy during the first decade of the nuclear era (1945–1955) at the national laboratories of several countries, under the control of the military. The first reactors, fueled with natural uranium, were used to produce plutonium for weapons use. Shortly thereafter, the U.S. decided to use an enriched uranium fueled, light water cooled reactor, an LWR, for submarine propulsion. In the prevailing Cold War atmosphere, the development of nuclear powered submarines had very high priority. The pressurized LWR was chosen over several competitors for the submarine reactor because it employed "familiar" technology (liquid water and steam) and because it was capable of very high power density.

When, in 1953, the race for dominance in the area of civilian nuclear power was set in motion by the Atoms for Peace program, and the U.S. needed a rapid response to counter the British (commercial) and Soviet (propaganda) threats, the LWR was the obvious choice. Research into the use of reactors for civilian power production, although widespread, was still exploratory and unfocused, and no other U.S. reactor design was ready for deployment as quickly.

The LWR had a number of features in its favor. It had benefited from continuing research and development in the Navy's ship propulsion program, and there were manufacturers familiar with the required technology. It used enriched uranium, which was, for a time, a U.S. monopoly, and therefore gave American manufacturers an important competitive advantage with respect to potential competitors (France, England, and the Soviet Union). The U.S. hegemony in this area was further strengthened by a series of bilateral "Agreements for Cooperation" in which the U.S. provided loan funds which could be used only for the purchase of equipment, materials (including enriched uranium), and technical services from U. S. nuclear vendors.[7] This reinforced the Official Technology status of the LWR throughout most of the Western Bloc countries.

Although the LWR had been placed in a privileged position by the political situation, it had significant shortcomings, many of which were apparent from the beginning. It had low thermodynamic efficiency with little potential for improvement. Fuel burnup was limited. It was considerably less forgiving of mechanical or operational error than such competitive designs as the molten salt reactor and the gas-cooled reactor. The LWR's necessary complexity (required to provide defense-in depth) implied "economies of scale" such that it could be economically competitive, if at all, only in very large sizes. These disadvantages were obvious enough to show that the LWR would be a poor choice to play the central role in nuclear generation strategies. Its shortcomings were tolerable only because the LWR was originally intended for a stop gap role, to be substantially phased out by the breeder by 1990.

Development of the breeder was the overarching goal of the scientists involved in both the military and civilian development of nuclear power. There was a pervasive belief that uranium was a very limited resource, so limited that weapons production would be seriously impacted and significant civilian use would be impossible.[8] Nuclear power proponents saw themselves in a race with fossil power generation schemes, and so needed a way to expand the number of nuclear power plants rapidly enough to gain market share and then to keep up with the anticipated very rapid rise in electricity demand. But not just any breeder would do. Because of the anticipated rapid growth of nuclear capacity, it would not be sufficient to breed at a rate capable of merely replenishing the fissile material burned. A "fuel factory" was needed which would produce enough excess plutonium not only to sustain itself but also simultaneously to produce enough additional plutonium to serve as seed stock for a rapidly growing fleet of similar reactors.

The measure of the ability to function as a fuel factory, not just as a self-sustaining reactor, is the "doubling time,"[9] and only the LMFBR had, at least in theory, the ability to achieve a short enough doubling time. The LMFBR performs best with an initial charge of plutonium to start the breeding process, which could be provided by extracting plutonium from spent LWR fuel, using methods and facilities similar to those developed for the weapons program. Thus, the LWR/LMFBR combination was thought to provide the most rapid path to a self-sustaining nuclear cycle.

Even when it finally became obvious that uranium availability would not constrain the growth of nuclear power, the U.S. Atomic Energy Commission (AEC), and later the U.S. Department of Energy (DOE), remained firmly committed to the original plan, using both strategic and economic arguments against any alternative to the LWR/LMFBR vision of the future. In 1969, Milton Shaw, director of the USAEC's Division of Reactor Development and Technology, in a foreword to a study of alternative breeder reactors, wrote

> The widespread acceptance of the light water reactor is an established fact. The large industrial commitments and improvements in technology should result in further improvements in performance. These factors will make difficult the introduction in the United States of any new system even though a potential economic gain is indicated. *Because of the urgent need to introduce breeder reactors at the earliest date*, the USAEC has committed itself to an extensive program involving LMFBR's. For this reason, development funds for competing concepts are limited. The possible role of such reactors in the U.S. nuclear power economy is, therefore, not yet clear.[10] [italics added]

The degree of unwavering government support for its vision of the nuclear future is exemplified by the AEC's 1973 (!) estimate that, by the year 2000, the U.S. would get half its electric power from 400 breeders and 600 LWRs.[11] Only 41 reactors were ordered after 1973 and every one was subsequently canceled, as were nearly 70% of those ordered after 1970.[12] In 1998 there are 103 licensed plants, all LWRs, and the number is expected to decrease substantially in the next decade.

The U.S. utility industry was also advocating early introduction of the LWR. In 1970, a General Electric Company vice president, recalling the reasons for the decision to offer the "turnkey" loss-leader plants that started the nuclear stampede in the United States, said

> If we couldn't get orders out of the utility industry, with every tick of the clock, it became progressively more likely that some competing technology would be developed that would supersede the economic viability of our own. Our people understood that this was a game of massive stakes, and that if we didn't force the utility industry to put those stations on line, we'd end up with nothing.[13]

The strategy of a rapid buildup of LWR power generating capability, followed by an equally rapid conversion to reliance on LMFBR's had a compelling technological logic. It had an equally attractive economic logic for the industrial participants who were eager to begin profiting from their enormous investments in nuclear technology.[14] Unfortunately, for both the U.S. and those who followed the U.S. lead, both logical analyses were wrong because the underlying axioms and assumptions were untrue.

The price now being paid for these errors is enormous in terms of both financial loss and lost opportunity. The financial loss is almost incalculable; it has been called the greatest managerial disaster in business history.[15] Moreover, even in countries where it has eventually failed, the LWR, by virtue of its Official Technology status, stifled the development and introduction of safer, cheaper nuclear power plants that might have taken advantage of modern technology and been better suited to contemporary constraints and the specific needs of various countries.

CURRENT STATUS OF THE LWR/FBR NUCLEAR POWER PARADIGM

The cost and complexity of the systems needed to deal with the danger of severe accident makes the LWR a poor choice for large central station power plants. Ironically, it is the LWR's high power density, the very reason it was chosen for submarine use, that is its Achilles heel. Even a 10-second interruption in the supply of cooling water at the surface of a fuel rod can lead to local overheating and irrevocable, cascading damage to the reactor core. As a result, the LWR must rely on defense-in-depth, a system of diverse and redundant backup devices, to guard against such an event. This is a widely used technique, but defense-in depth cannot, by itself, guarantee absolute safety; it can only reduce the probability of a serious accident. All nuclear power plants, because of their cost and potential for off-site hazards, have a very low "acceptable" probability of failure. The larger the plant, the lower the acceptable probability of failure. Because the consequence of failure is so large in gigawatt-scale plants, LWR's have been forced to employ engineered safety systems that promise unprecedentedly, and perhaps unattainably, low probability of failure.

The first LWRs employed defense-in-depth systems which were calculated to achieve failure probabilities of 10^{-4}/year or less (i.e., an expected mean time before a major accident, such as core meltdown, of at least 10,000 years, for a single, given reactor). This is a commonly accepted level of risk for high capital cost industrial facilities from the standpoint of investment protection. However, it is clearly inadequate from the perspective of public safety for the case of nuclear reactors.[16] As a result, all reactors were required to have a confinement dome to protect the public, in addition to the engineered safety features which were of high-level industrial grade. It was clearly prudent to have such an extra level of protection for a new technology with possible unexpected failure modes, and largely ill-understood consequences. The resulting risk of a given reactor undergoing a major accident with public health consequences was believed to be less than 10^{-6}/yr, with the confinement dome playing a major role in reducing the consequences of the accident. This arrangement made perfect sense for the first generation of 200–400 MWe LWR's, but set a subtle trap for the next and successive generations of much larger reactors.

The complexity of defense-in-depth safety systems leads to size-independent costs that are better borne if the costs are supported by the revenues of a larger power plant. This factor, in combination with the scale economy of steam generators and turbines, and the more difficult than anticipated competition with low cost fossil fuel, led to a very rapid scale up of LWR size. But above about 500–600 MWe, engineers could no longer guarantee the integrity of the confinement system.[17] It was not realized, until it was too late to modify development plans, that the inability to build a confinement vessel that could withstand a major accident in such a large reactor violated the initial safety concept. Because the confinement vessel could not be counted upon, defense-in-depth would have to be solely responsible for public safety. This meant that failure probability levels of 10^{-6}/year, that is, a mean time before major accident of one million years, had to be achieved for the reactor itself, without reliance on any additional safety credit for the dome. This unprecedented level of safety for a defense-in-depth system, when applied to so complex a system as a nuclear reactor, meant that the safety system itself had to be enormously complex, which made it maintenance-intensive, and, as it happened, actually more problem prone than the device it was meant to protect. As a result, LWR power plants are expensive, complex, difficult to operate, and incapable of simultaneously competing with fossil fuels and achieving the desired level of safety. All of these problems are attributable, at least in part, to the reliance on defense-in depth. However, despite all the attention given to the safety system, the public remains unconvinced of the safety for which so high a price is paid. This skepticism is well justified because insufficient data is available to calculate the true probability of a major accident and it is literally impossible to demonstrate, by definitive test, that the requisite level of safety has been achieved.

The sodium-cooled LMFBR was the device that was intended to replace the LWR when mined uranium supplies became prohibitively expensive. The LMFBR was chosen over other breeder reactor designs because it was, in theory, capable of very short fuel doubling times, shorter than that of any competing reactor design. The doubling time is the time required to produce an *excess* of fuel equal to the amount originally required to fuel the reactor itself. In other words, in one doubling time there would be enough fuel available to start up another reactor. In the absence of mined uranium, only a short doubling time would, it was believed, allow nuclear power to grow fast enough to compete with alternative sources of power.

Unfortunately, the theoretical advantages of the LMFBR could not be achieved in practice. A successful commercial breeder reactor must have three attributes; it must breed, it must be economical, and it must be safe. Although any one or two of these attributes can be achieved in isolation by proper design, the laws of physics apparently make it impossible to achieve all three simultaneously, no matter how clever the design. The fundamental problem originates in the very properties of sodium that make the short doubling time possible. The physical characteristics of sodium and plutonium are such that a loss of sodium coolant in the center of the core of a breeding reactor (caused, for example, by overheating) would tend to increase the power of the reactor, thus driving more sodium from the core, further increasing the power in a continuous feedback loop. The resulting rapid, literally uncontrollable, rise in reactor power is clearly unacceptable from a safety standpoint. This effect, the so-called "positive void coefficient" can be mitigated by, for example, changing the shape of the core so that more neutrons leak out of the core, but this immediately compromises the reactor's breeding potential. Safety and breeding are thus mutually antagonistic. This situation can be alleviated to some extent by making radical design changes, but these changes lead to greatly increased costs, and make the reactor prohibitively expensive.

Even if the LMFBR could meet its original, highly optimistic, operating goals and the LWR/FBR power cycle were put into operation, it is unclear that the goal of energy security would be achieved. As discussed in the following sections, the measures that would have to be put in place to protect all parts of the fuel cycle against terrorism would have very high social costs. Equally important is the increased risk of accidental or maliciously-induced technological failure. Compared to light water reactors operating on the once-through fuel cycle, the breeder fuel cycle is much more complex and error-prone. This implies a higher probability that the entire nuclear system or a significant fraction thereof might need to be shutdown because of a generic problem, for example, with sodium containment, in the reactors or an accident in one of the reprocessing or fuel fabrication plants that serve the system.

LARGE-SCALE BREEDER DEPLOYMENT

The standard energy security rationale for breeder deployment in countries with small indigenous uranium resources, such as Japan, is based on their low feedstock uranium fueling requirement—a factor of about 100 less than an LWR of the same capacity operating on a once-through fuel cycle. The argument is that this makes a breeder-based nuclear supply system invulnerable to potential cutoffs in the supply of imported uranium and to the associated threat to societal stability which might accompany electricity shortfalls. However, this perspective on energy security is too narrow. There are societal risks associated with breeder deployment which tend to negate the advantage of independence from uranium supply, and may even make the situation worse. In the following we discuss the nuclear proliferation, terrorism, and accident risks associated with the breeder fuel cycle and then outline a strategy for energy security based on "converter" reactors (primarily LWRs, for the next several decades,) operating on once-through fuel cycles, which minimize such risks.

To get a quantitative sense of the potential scale of breeder deployment in a country such as Japan, we assume that utilization of nuclear power is one component of an energy strategy designed to minimize the risks of greenhouse warming. To be concrete, we assume that future nuclear deployment in Japan is consistent with the nuclear-intensive, low carbon dioxide energy supply system (LEES) scenario, developed by the Intergovernmental Panel on Climate Change (IPCC).[18] This scenario is based on an approximate 10-fold growth in global nuclear capacity from 330 GWe in the early 1990s to 3,300 GWe in the year 2100.

In Japan, the government has recently announced plans to reduce carbon dioxide emissions by the construction of 20 additional nuclear reactors by early in the next century. This would increase installed nuclear capacity to about 70 GWe from the current 40 GWe. Consistent with the global nuclear-intensive LEES scenario, we assume conservatively that there is a further increase of nuclear capacity to 100 GWe by 2100. If this capacity consists of liquid metal fast breeder reactors (LMFBR) of standard design, the associated plutonium flow would be approximately 200 tonnes per year.

Nuclear Proliferation

The basic problem here is that the breeder fuel cycle involves very large flows of plutonium which, because they are not associated with fission products, can be processed by chemical means into weapons-useable nuclear material in a straightforward manner. If the breeder core and blanket spent fuel are reprocessed together, the separated plutonium is "reactor-grade," that is, it contains larger amounts of the even-numbered plutonium isotopes compared with the "weapons-grade" plutonium traditionally used in nuclear weapons. There has been considerable controversy about the usability of reactor-grade plutonium in nuclear weapons since the beginning of the nuclear age. However, the fact that such plutonium can be used to make nuclear weapons at all levels of technical sophistication has recently been declassified by the U.S. Department of Energy.[19] In particular, subnational groups could build first-generation fission bombs, using 5–10 kg of reactor-grade plutonium, which have an assured yield of one or a few kilotons, and, at the other end of the design sophistication spectrum, technologically-advanced states could build two-stage thermonuclear weapons using even smaller amounts of this material.

Thus, the very large flows of plutonium associated with large-scale breeder deployment entail serious risk of diversion for weapons by both states and subnational groups. This is hardly a new insight: the inadequacy of a nonproliferation regime which relies solely on international inspection of nuclear facilities to prevent state diversion of weapons-useable materials was stressed in the Acheson-Lilienthal Report of 1946 that became the basis of the Baruch Plan for international control of nuclear weapons submitted to the United Nations by the U.S. the same year.

> There is no prospect of security against atomic warfare in a system of international agreements to outlaw such weapons controlled only by a system which relies on inspection and similar police-like methods. The reasons supporting this conclusion are not merely technical, but primarily the insuperable political, social, and organizational problems involved in enforcing agreements between nations each free to develop atomic energy but only pledged not to use bombs. . . . So long as intrinsically dangerous activities [i.e., production and use of weapons-useable

> materials such as plutonium and highly-enriched uranium] may be carried out by nations, rivalries are inevitable and fears are engendered that place so great a pressure upon a system of international enforcement by police methods that no degree of ingenuity or technical competence could possibly hope to cope with them.[20]

Today, with the growth of support for the goal of global nuclear disarmament embodied in Article VI of the Non-Proliferation Treaty (NPT), this conclusion is just as salient as it was in 1946. Indeed, there is a widespread consensus, which even includes many supporters of nuclear power, that the risk of nuclear weapons "breakout" in a world where such weapons are banned but nuclear power is widely deployed would be too great unless all "dangerous activities" such as spent fuel reprocessing are clustered in "nuclear parks," subject to both stringent physical security and international safeguards, and, constituting the greatest departure from current practice, are also under international or multinational control.

Presumably, such arrangements would reduce the risks of both proliferation by the host country as well as subnational diversion. But what are its implications for energy independence in a country such as Japan?

Obviously, the answer depends on the specific institutional arrangements which govern the management of the facility.[21] However, the freedom of action of the individual states would inevitably be constrained to some degree: this is, after all, the primary rationale for placing sensitive nuclear facilities under international or multinational control. Consider, for example, a large multinational fuel reprocessing plant, for example, one with a throughput of 1000 tonnes of spent breeder fuel, located in Japan, which serves all of Japan's breeder reactors, say 100, as well as several additional units in other countries in East Asia. In the event of, for example, the discovery by the International Atomic Energy Agency (IAEA) of a large amount of material unaccounted for (MUF) or of a serious accident, the organizational entity in charge of plant operations might well decide to shut the plant down until the source of the MUF or the cause of the accident is determined and remedial actions are taken. However, the Japanese government would likely be reluctant to cede decisions regarding the operation of a facility which is critical to its nuclear energy supply to a body which it does not control.

Nuclear Terrorism

The implications for energy security of measures that might be considered necessary to deal with the threat of subnational diversion of a very small fraction of the plutonium associated with large-scale breeder deployment are even more serious. Given the potentially catastrophic consequences of such a diversion, for example, detonation of a crude fission bomb fashioned from 5–10 kg of reactor-grade plutonium could cause death and destruction by airblast alone over an area more than 60 times greater than the recent Oklahoma City explosion in the U.S.,[22] it would be difficult to argue against the use of stringent, perhaps draconian, measures to prevent such diversions in the first place, and, if these fail, to search for and recover the plutonium before it could be fashioned into weapons.

The concern is that such measures would have an adverse impact on the civil liberties of citizens in democratic states and would cause significant societal stress. Before plans for large-scale separation and use of plutonium in the nuclear fuel cycle, the focus of civil liberties concerns were security measures designed to prevent sabotage of commercial nuclear reactors with the possible release of large amounts of radioactivity. However, it is the large-scale use of plutonium, with its associated transport of material, which offers the best opportunity for nonstate adversaries, for example, terrorists or criminal organizations working with disaffected insiders, to obtain weapons-useable nuclear material, which forces the consideration and possible implementation of additional security measures with potentially much greater civil liberties impact.[23]

Obviously, the impact depends on the scale of plutonium use and on the degree of collocation of reprocessing and MOX fuel fabrication facilities. Although collocation would eliminate the transport of plutonium oxide off-site and thus reduce the risk of diversion of this material, there would remain the need for covert surveillance of nuclear plant employees and of outsiders regarded as likely to steal plutonium, and of emergency searches and seizures to recover diverted plutonium. The acceptability of such measures in a democratic society is a function both of the society's political and cultural norms as well as whether it can meet its energy needs without recourse to plutonium use.

Thus, paradoxically, the attempt to assure societal stability by implementing a breeder-based nuclear supply system could lead to severe societal stresses because of the potential civil liberties impact of measures required to keep plutonium out of the hands of criminals and terrorists.

Technological Failure

A breeder-based nuclear supply system is inherently more complex and error prone than one based on LWRs operating on a once-through fuel cycle. Not only does the breeder system have complex components which have no counterpart in an LWR system, for example, reprocessing plants, but even when a counterpart exists, for example, the reactors themselves, fuel fabrication plants, and a transportation network, they are more complex in a breeder-based system. Aside from the reactor, much of this added complexity is due to the radiological hazards, criticality risks, and security threats associated with the presence in the breeder fuel cycle of large quantities of unirradiated plutonium, that is, plutonium without fission products. Actual failure of, or just loss of public confidence in, any component of the breeder fuel cycle could shut down a significant part of, or even the whole system, thus negating its potential energy security advantage. In the following, we comment briefly on the technological vulnerabilities of breeder reactors and the associated reprocessing and fuel fabrication plants.

Proponents of the LMFBR have made many claims regarding the robust engineering base of sodium reactor technology, but experience around the world has demonstrated that sodium cooled systems often suffer serious disruptions even in the event of relatively minor failures.[24] The potential for sodium-air and sodium-water reactions accounts for some of this sensitivity, and the problem is exacerbated by the opacity of sodium, which makes fault detection substantially more difficult for such systems than for those in which visual inspection is possible. These technological problems, in addition to the design difficulties associated with the tension between breeding and safety, strongly suggest that any large-scale LMFBR would be more problem-prone than the current generation of LWRs.

Large plants for reprocessing LWR spent fuel in France and England have achieved high capacity factors in recent years. However, the radioactive effluents emitted by such plants during normal operation, and the accumulating stocks of separated plutonium as well as high-level and transuranic wastes are a source of growing concern among the public, the media, environmental groups, and bureaucracies in many countries. Moreover, because of the much higher fissile content and burnup of breeder compared with LWR spent fuel, reliable operation of breeder reprocessing plants will be more difficult and costly. That is, breeder plant equipment must be smaller to ensure criticality safety, the contact time between the extraction phases must be shorter to avoid radiative decomposition of process materials, and the need for higher fission product decontamination increases the volume of liquid waste streams. Similar remarks apply to plutonium fuel fabrication; as with reprocessing, fabrication of LMFBR fuel is more demanding than making MOX fuel for LWRs.

In sum, while the potential risks of both nuclear proliferation and terrorism as well as technological failure associated with a breeder-based nuclear supply system are difficult to quantify, they appear to be substantially greater than those associated with the current LWR-based system. Thus, in light of the strong adverse societal response to relatively minor mishaps with the present system, the chances and consequences of failure of any portion of a breeder-based system are too large to warrant reliance on it for a significant fraction of Japan's electricity requirements. But is it possible to achieve energy security via nuclear power without the breeder? We believe that the answer is yes, and that the essential element is uranium stockpiling.

URANIUM STOCKPILING

In the following we comment briefly on three issues: (1) the availability of conventional, that is, terrestrial, uranium resources; (2) the feasibility for a country such as Japan to stockpile sufficient imported uranium to operate a large nuclear supply system based on current light water reactors or advanced converters for many years on the once-through fuel cycle; and, (3) the feasibility of extracting uranium from seawater.

Conventional Uranium Resources

The worldwide availability of conventional uranium resources at a given price depends on the geologic resource base, the available extraction technology, and environmental and political constraints on uranium mining or export. In the last 100 years there have been many forecasts of future shortages or increases in the cost of various elements, for example, copper, zinc, and uranium. In most cases, such forecasts have proven false because of new discoveries as well as improved technologies for the mining and milling of such materials. In the specific case of uranium, prices today are lower (when adjusted for inflation) than they have ever been.

Part of this is due to the depressed market for nuclear power, part is due to the recent discovery of very rich deposits in Canada, Australia, and states of the former Soviet Union, and part is due to better technology such as in-situ leach mining and the process of jet-boring in frozen ground to allow uranium ore to be extracted from underground and pumped as slurry to the surface without human contact.

Recent OECD/IAEA projections of uranium recoverable at various prices (1995 "Red Book") indicate significant resource increases in most price categories compared with projections made in 1993 despite the fact that, because of the lack of demand, exploration activities have decreased in most countries surveyed. Thus, the current estimates of a resource base on the order of 30 million tonnes—enough to supply current global nuclear capacity for more than 400 years—should be considered as conservative, given both the lack of incentive to better estimate higher cost resources and the fact that not all countries provide data on uranium resources.

Noteworthy with regard to the former point is that mining evidence suggests a 300-fold increase in the estimated amount of recoverable uranium for every 10-fold decrease in ore grade.[25] Furthermore, even if the cost of uranium from low-grade ores is substantially greater than the current price, the impact of higher uranium costs on the total cost of nuclear power will be small. For example, the current price of natural uranium (about $20/kg) corresponds to a contribution to the cost of electricity generated by current generation light water reactors of about 0.05¢/kWhr, or about 1% of the busbar cost. Thus, even a 10X increase in the price of uranium cost would only increase the busbar cost by about 10%.

In sum, terrestrial uranium at affordable prices is far more available than anyone imagined 20 to 30 years ago. However, from a strategic perspective, the distribution of uranium resources is very uneven, with most of the resource concentrated in a few countries. Thus, states with large nuclear ambitions but essentially no indigenous uranium, such as Japan, may be uneasy about the security of uranium supply for LWRs even with maximum diversification of supply sources and with involvement in uranium exploration and development of new mines in other countries. Two promising ways to improve this situation are to establish a strategic uranium reserve by stockpiling and to further develop the technology for mining uranium from seawater.

Establishing a Strategic Uranium Stockpile

The world glut in natural uranium is now compounded by the prospect of hundreds of tonnes of highly-enriched uranium (HEU) being recovered from dismantled U.S. and Russian nuclear warheads and becoming available as low-enriched uranium (LEU) fuel for light water reactors. The U.S. and Russia have already concluded a deal in which 500 tonnes of Russian HEU will be blended down to LEU and sold to the U.S. over the next 20 years, and additional comparable amounts of HEU from dismantled weapons could become available in both Russia and the U.S.

However, even without access to blended-down weapons HEU, there are adequate natural uranium resources and uranium enrichment capacity available to a country such as Japan to acquire a strategic uranium reserve of either natural uranium or LEU fuel to provide a supply of fuel to weather any realistic supply interruption.[26] For example, to create a stockpile of yellowcake sufficient to supply all the currently operating LWRs as well as those now under construction in Japan for 10 years would cost less than \$1.5 billion in constant year 1998 dollars.[27] This is substantially less than the cost of a single breeder reactor. Alternatively or concurrently, LEU fuel could be stockpiled to take advantage of the current worldwide oversupply in uranium enrichment services. Although, in theory, access to enrichment services could be curtailed, Japan has demonstrated indigenous capability in uranium enrichment via gas centrifuges. which could be rapidly expanded. Stockpiling yellowcake and relying on foreign or indigenous enrichment capability has the advantage of providing a degree of flexibility in the choice of product enrichment levels to accommodate projected future increases in fuel burn-up in LWRs or the requirements of advanced reactors.

Of course, other energy resources, such as coal, could also be stockpiled, but here uranium has significant advantages: (1) the cost is low (about one-tenth that of coal for equivalent energy), and (2) storage is easy (more than four orders of magnitude less mass than the mass of coal for equivalent energy). Furthermore, uranium, unlike coal, will not degrade in storage.

Mining Uranium from Seawater

Seawater uranium at an affordable price is the ultimate guarantee of uranium availability for any nation with access to the ocean. Because of the very large amounts of uranium in the oceans—about four billion tonnes, or about 800 times more than the terrestrial resources recoverable at a price of \$130/kg or less—the possibility of recovering uranium from seawater has received considerable attention over the past four decades. The major drawback is the fact that the uranium concentration is very low, about 3 ppb. This implies that the extraction cost will be high unless the uranium recovery efficiency from seawater is high and adequate seawater flows can be established without active pumping. Ongoing R&D efforts in Japan over the last decade on uranium adsorbents and seawater processing schemes have met this challenge; both the technical feasibility and economic viability of the process have been established. For example, the most recent (1993) cost estimate was about 40,000 yen per kg of recovered uranium, equivalent to about \$100/lb U_3O_8 (U.S.\$1 = 125 yen).[28] Although this is about 10X the current market price of uranium, it would increase the busbar cost of LWR electricity by only 10%, and that of more efficient reactors by even less. The resulting electricity cost would be highly competitive with the cost of electricity from a breeder reactor even under the most optimistic estimates of the capital cost differential between the breeder and the conventional LWR.

There is a long history of research and development on extracting uranium from seawater in Japan, and current plans include progressively larger ocean tests of the technology up to commercial scale. A large experimental pilot plant was operated in 1986/87 using hydrated titanium oxide particles as the adsorbent in a conventional fluidized bed. About 15.5 kg of uranium was extracted. In the late 1980s a much faster adsorbent was developed and tested. It consists of very fine powders of amidoxime embedded in the fine fibers of a supporting material, such as polyethylene with silica, which can be made into nets or blankets. Since this structure is full of voids, seawater can pass through it with relatively low loss of water head. By this means, moored adsorption systems utilizing rapid natural ocean currents can be constructed as an alternative to pumping seawater. Such rapid flows improve the adsorption rate. In a recent test, units containing fibrous amidoxime adsorbents placed at various depths under the sea were able to recover 1 kg of uranium per tonne of adsorbent in 20 days, and 2 kg/tonne in 60 days.[29]

A POSSIBLE COURSE OF ACTION

Near Term (1998–2001)

This period could be used to reassess the state of nuclear power and to develop an innovative plan for future nuclear development that takes advantage of new realities with respect to resource availability and developments in technology since the original LWR-FBR strategy was put in place. The most important tasks will be to: (1) assure safe and efficient operation of the existing LWR fleet as well as any additional reactors using LEU fuel on the once-through cycle; (2) avoid further commitments to the extraction and use of plutonium; (3) develop plans for establishing a uranium stockpile based on low-cost terrestrial resources; and (4) continue vigorous research and development of seawater uranium extraction systems leading to the eventual test of a system capable of extracting several hundred tonnes of yellowcake.

Specific actions in (1) include demonstration and use of higher burnup fuels which reduce the amount of spent fuel generated per unit of electricity produced, and development of plans for long-term storage of such fuel both within the borders of Japan and possibly under international auspices. While higher burnup fuels require higher levels of initial enrichment, these costs may be offset by the availability of cheaper separative work via laser enrichment. In theory, this could have a negative impact on proliferation since once the use of lasers to enrich to LEU levels is demonstrated, it will also become clear how to adapt the technology to make HEU, and also turn reactor-grade plutonium into weapons-grade by separating the even and odd plutonium isotopes. However, gas centrifugation, a proven method for making LEU, HEU, and separating the plutonium isotopes, already exists, and, as previously noted, reactor-grade plutonium can be used to make nuclear weapons at all levels of technical sophistication. Thus, even if it is eventually implemented to produce LEU for commercial reactors, laser enrichment will not significantly increase the existing technical potential for proliferation.

Factors which need to be considered with regard to (2) include the size of the reactor fleet, the risk of a possible cutoff, and the price to be paid for such insurance. In this connection, we note that the only examples of past cutoffs in the supply of nuclear materials and technology from, for example, the United States and Canada to India and Pakistan, have been based on noncompliance with nonproliferation norms. On this basis, a similar cutoff of Japan, one of the pillars of the nonproliferation regime, seems remote.

It may also be possible in the near term to decide whether to make a major investment in the development of the High Temperature Reactor (HTR). This decision can utilize the experience gained in construction of the High Temperature Test Reactor (HTTR).[30] However, it is important to realize that there have been many significant technical developments in this area since the HTTR was designed. The most important of these is the modular concept which limits size and power density to achieve inherent safety. Developments in high temperature materials and high performance turbomachinery are almost equally significant. Modern conceptual designs done in Japan[31] and elsewhere[32] show the potential of the HTR for deployment within Japan as well as providing a significant export market for Japan's manufacturing capabilities in turbomachinery and heat exchangers.

Intermediate Term (2001–2010)

This period can be used to implement the decisions made in the near term, and to set in place plans for the long-term role of nuclear power in the production of electricity and process heat. The most important early action will be completion of the commercial scale test of seawater uranium extraction. If successful, the technology could then be put "on the shelf" as insurance to be used in the case of a cutoff in the supply of uranium. Experience with the pilot plant will allow accurate estimation of the time needed to deploy enough plants to maintain Japan's nuclear power industry in the event of total cutoff. Implementation of a seawater extraction system on a scale needed to supply uranium for a fleet of, say, 100 LWRs would be a major task. However, the same independence from imports of uranium as promised by the breeder could thus be achieved at much lower economic and sociopolitical cost, with lower risk of failure.

If the potential of the High Temperature Reactor-Gas Turbine (HTR-GT) is verified by the near-term studies, the intermediate term can be used to put in place the manufacturing infrastructure for serial production of these reactors and their specialized fuel. Because each unit will be limited in output to 200–250 MWth, fleet sizes and manufacturing facilities will be comparable to those in the commercial aircraft industry, with comparable economic consequences.

The intermediate term should also be the period in which the full range of potential embodiments of nuclear power is considered for eventual development. Especially if large-scale implementation of uranium seawater extraction encounters serious problems, it would be prudent to explore the prospects for a safer, less complex, more proliferation-resistant breeder than the standard LMFBR. Indeed, there already has been considerable research and development of such a concept, the Integral Fast Reactor (IFR). The key feature of the IFR fuel cycle is the use of pyroprocessing rather than the standard PUREX process to effect a clean separation of the actinides from the fission products in the spent fuel in a facility adjacent to the reactor. The actinide-free waste would be disposed of in a geologic repository, while the actinides, along with some fission products, would be recycled back to the reactor. Although the concept is attractive, we believe that its claimed advantages with regard to reduction of the waste hazard and greater proliferation resistance have been oversold by its proponents. Moreover, the ability to effect a clean separation of the actinides from the fission products and to burn the actinides, including the neptunium, americium, and curium, remains to be demonstrated.

Thorium fuel cycles have also been promoted on the basis of lower long-term waste toxicity and greater proliferation resistance, but, as above, there may be less here than meets the eye. The initial rationale for introduction of the thorium cycle was the perception that it was more abundant than uranium, and that it could be used to breed U-233, an isotope with superior properties for use in thermal reactors. However, its terrestrial abundance is not germane to Japan's energy security concerns because Japan has no indigenous source of thorium, and it is hard to imagine a scenario in which uranium is cut off but thorium is available. Conceivably, the use of U-233 in an advanced reactor could reduce the possibility of a common mode failure of a reactor fleet consisting of LEU-fueled LWRs and HTGRs. The Molten Salt Reactor would be a strong candidate for consideration for this role, with a solid research base and an international support group,[33] but other thorium-fueled concepts should also be considered.[34]

Long Term (2011–)

In this time frame, the costs and benefits of continued reliance on fossil fuels and the potential for large-scale utilization of renewable resources should become much clearer. This will provide a more realistic perspective on the need for nuclear power including the preferred technological embodiments and international institutional frameworks for dealing with safety and proliferation concerns. The role of nuclear power, decisions as to the optimal makeup of the power reactor fleet, and the degree of reliance upon seawater-derived uranium can be postponed until the technical, economic, and political issues are better resolved. However, it is of paramount importance to ensure that current actions do not unreasonably prejudice support for a nuclear component of energy supply. Strong support for plutonium recycle, with its associated technical risks and societal costs, in the face of increasing evidence that alternative strategies are superior, is clearly counterproductive. The advantages with respect to energy security of such a fuel cycle can be achieved at much lower technical, economic, and sociopolitical costs by stockpiling terrestrial uranium and developing the technology for extracting uranium from seawater.

NOTES AND REFERENCES

1. The linkage between nuclear power and nuclear weapons includes both the use of a peaceful program as a cover to gather resources for a separate, covert weapons program as well as the diversion of weapons-useable materials such as plutonium by both rogue states and subnational groups.

2. The LWR has a limited export market because of the high capital cost of large units and the demands this complex technology imposes on the societal infrastructure for its safe operation.

3. R. V. Davies et al., "Extraction of Uranium from Seawater," *Nature* 203 (1964): 1110.

4. Unfortunately, this work, which includes theoretical studies, laboratory tests, and pilot plant operation, is not well-known, even in the nuclear community, outside Japan, mainly because most of the publications are in Japanese. For example, recent ocean tests of advanced uranium adsorbents are reported in: T. Sugo, "Status of Development for Recovery of Uranium from Seawater," *Bulletin of Seawater Science of Japan* 51 (1997): 20.

5. Steven M. Cohn, *Too Cheap to Meter: An Economic and Philosophical Analysis of the Nuclear Dream* (Albany, NY: State University of New York Press, 1997). Chapters 3 and 5 describe the history and benefits of "Official Technology" status for nuclear power. Chapter 6 discusses the loss of OT status and its effects on the U.S. nuclear program.

6. For IAEA estimate, see J. Kupitz, "*Rationale for Thorium Introduction*" (Advisory Group Meeting on Thorium Fuel Perspectives, Vienna, Austria 16–18 April 1997).

7. I. C. Bupp, J.-C. Derian, 1997. *Light Water: How the Nuclear Dream Dissolved* (New York: Basic Books): 15–41.

8. J. G. Morone, E. J. Woodhouse, *The Demise of Nuclear Energy?: Lessons for Democratic Control of Technology* (New Haven: Yale University Press, 1989): 29–34.

9. The doubling time is the time required to double the amount of fissionable material available under the assumption that all fissionable material is used as breeder fuel as soon as it becomes available in suitable form. The doubling time must account for time spent in the reactor core, time spent in reprocessing and refabrication, as well as any necessary decay periods for spent fuel before reprocessing. Factors favoring a short doubling time include efficient neutron utilization, high specific power, and rapid recycle of spent fuel. All of these factors increase the risk and cost of the LWR/FBR system.

10. M. Shaw, *An Evaluation of Alternate Coolant Fast Breeder Reactors* (USAEC document WASH-1089, April, 1969): Foreword.

11. William Lanouette, "Nuclear Power in America: 1945–1985," *The Wilson Quarterly*, 9:5 (Winter 1985): 90–133 (cited on page 120).

12. U.S. Department of Energy, *Commercial Nuclear Power, 1991* (DOE/EIA-043891).

13. Steven M. Cohn, Op. cit., p. 32.

14. Op. cit., pp. 73–74.

15. James Cook, "Nuclear Follies" *Forbes*: 135(3) (Feb. 11, 1985): 82–100.

16. The cumulative public risk depends on the size of the reactor fleet. One hundred reactors, each with an annual probability of major failure of 10^{-4} per year, would have a cumulative failure probability of 10^{-2} per year.

17. J. G. Morone, E. J. Woodhouse, Op. cit., pp. 78–82.

18. H. Ishitami et al., "Energy Supply Mitigation Options," chapter 19 in *Climate Change 1995*, eds. R. T. Watson et al. (Cambridge, Eng.: Cambridge University Press, 1996).

19. *Nonproliferation and Arms Control Assessment of Weapons-Useable Fissile Material Storage and Excess Plutonium Disposition Alternatives*. (U.S. Dept. of Energy, DOE/NN-0007, 1997): 37–39.

20. *A Report on the International Control of Atomic Energy* (Washington, D.C.: U.S. Government Printing Office, March 16, 1946).

21. For a comprehensive discussion of the technical, economic and institutional problems involved in setting up and operating international or multinational fuel cycle centers, see *International Arrangements for Nuclear Fuel Reprocessing*, eds. A. Chayes and W. B. Lewis (Cambridge, MA: Ballinger, 1977).

22. In 1995, a truck bomb containing about two tons of low-grade chemical explosives destroyed the Murrah Federal Office Building in Oklahoma City, Oklahoma, resulting in

the deaths of 168 people. The factor of 60 follows from the fact that the area of destruction due to airblast scales as the 2/3 power of the explosive yield.

23. There is a substantial literature on the civil liberties impact of nuclear power, particularly with regard to plutonium use. An old, but still useful report which explores three widely-held positions in U.S. society as to the civil liberties risks of plutonium use in the nuclear fuel cycle is: Alan F. Westin, "Civil Liberties Implications of U.S. Domestic Safeguards," Appendix III-C of Volume II of *Nuclear Proliferation and Safeguards* (Washington, D.C.: U.S. Office of Technology Assessment, 1977). A more recent assessment which emphasized the civil liberties risks of plutonium use in Japan is: Alexander Rossnagel, "Societal and Legal Implications of MOX Use, Part 2 MOX and Society," Chapter 6 in J. Takagi et al., *Comprehensive Social Impact Assessment of MOX Use in Light Water Reactors* (Tokyo, Japan: Citizen's Nuclear Information Center, Nov. 1977). Both of these references have extensive bibliographies.

24. Monju's recent shutdown was caused by the failure of a small thermocouple tube, leading to an air-sodium reaction. Similar incidents in light water reactors usually have negligible consequences.

25. K. S. Deffeyes, I. MacGregor, "World Uranium Resources," *Scientific American* 24(1) (1980): 66–76.

26. For a detailed assessment of the relative costs of a LWR-once-through system, using stockpiled uranium and a system based on reprocessing and recycle of LWR plutonium, see: P. Leventhal, S. Dolley, "A Japanese Strategic Uranium Reserve: A Safe and Economic Alternative to Plutonium," *Science & Global Security* 5(1) (1994): 1–31.

27. This assumes: (1) a requirement of 150 million lb of yellowcake for a system consisting of 42 GWe of LWRs with an average fuel burnup of 43,000 MWD/MT; (2) the yellowcake is acquired in equal amounts over a 10-year period starting in 1998 with no real increase over this period from the current spot price of $12/lb; and (3) a real discount rate of 5%/yr.

28. H. Nobukawa et al., "Development of a Floating Type System for Uranium Extraction from Seawater Using Sea Current and Wave Power" in *Proceeding of the 4th International Offshore and Polar Engineering Conference, Osaka, Japan, April 10–15, 1994*: 294–300.

29. See Ref. 3.

30. *Proceedings of the 2nd JAERI Symposium on HTGR Technologies, Orai, Japan, Oct. 21–23, 1992 (JAERI-M 92-215)* contain an overview of the HTTR project and detailed descriptions of selected aspects. These proceedings also discuss HTR status in several other countries.

31. K. Kunitomi et al., "Conceptual Design of 50 MW Severe Accident Free HTR and Related Test Program of HTTR," *Nuclear Technology* 123, September 1998, 245–258.

32. X. L. Yan, L. M. Lidsky, "Design of Closed-Cycle Helium Turbine Nuclear Power Plants" in *International Gas Turbine and Aeroengines Congress and Exposition, Cincinnati, Ohio, May 24–27, 1993. (ASME 93-GT-196).*

33. Prof. K. Furukawa is the driving force on a project to restart the development of reactors based on thorium molten-salt technology. The International Conference on

Thorium Molten-Salt Reactor Development took place in Santa Monica, California, USA, April 8–11, 1997. The Meeting was attended by 24 participants from Belarus, Czech Republic, France, India, Japan, Russia, Turkey, USA, and the IAEA.

34. An example of a once-through thorium cycle of considerable current interest utilizes an enriched seed-natural uranium/thorium blanket core configuration in a standard pressurized water reactor. For a comprehensive critique of this concept, see: P. R. Kasten, “Review of Thorium Reactor Concept,” *Science & Global Security* 7(2) (1998): 237–269.