The Breeder Reactor

by

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Summary

Development efforts worldwide have demonstrated that the plutonium fast breeder is uneconomical and will remain so in the foreseeable future. The benefits of the plutonium breeder, associated with its ability to more efficiently utilize uranium resources, are not diminished if breeder development is postponed for decades, and in the interim if the spent fuel from the existing conventional reactors is stored. In the near term the energy security benefits of the plutonium breeder can be achieved more cheaply and more quickly by stockpiling uranium. Deployment of plutonium fast breeders would entail staggering amounts of nuclear weapons-usable plutonium in the reactors and the supporting fuel cycle. There is no adequate means of safeguarding this material to prevent some of it from being used for nuclear weapons. The continued development of plutonium breeders in Russia will legitimize breeder programs and large plutonium stockpiles in non-nuclear weapons states.

1. Introduction[1]

A breeder is a nuclear reactor capable of creating fissile material faster than it is consumed. As power reactors, breeders once held out the promise of an essentially inexhaustible supply of low-cost energy. Thus, in 1945 Enrico Fermi predicted, "[t]he country which first develops a breeder reactor will have a great competitive advantage in atomic energy."[2] Fermi turned out to be wrong. He failed to appreciate what we now know: breeders simply cost too much - they are uneconomical. Fermi also failed to foresee the enormous risks that a breeder economy would pose for society. In this paper we will examine some of these risks. But first, for the benefit of those unfamiliar with breeder technology, we review some of the technical aspects that distinguish breeders from the more familiar light water reactors (LWRs) in wide use today. This is followed by a review of the status of worldwide efforts to develop the Liquid Metal Fast Breeder Reactor (LMFBR), the breeder technology of choice. After reviewing the risks associated with the LMFBR and its fuel cycle, we touch upon two of the arguments currently offered to justify further investment in breeder technology: that it provides greater energy security and improves waste management.

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[1] This paper is drawn from "The Plutonium Breeder," a earlier paper by the author presented at the International Conference on Plutonium in Omiya Sonic City, Japan, November 2-4, 1991.

[2] As cited in U.S. Atomic Energy Commission, "Cost-Benefit Analysis of the U.S. Breeder Reactor Program," WASH-1126, April 1969.

As we review these issues we should not forget that the primary purpose of nuclear power reactors is to generate electricity. The additional purpose of the plutonium breeder is to create plutonium, an alternative to uranium fuel. Plutonium fuel is important only if its use in reactors is economical, or as a hedge against insecure supplies of uranium fuel. Despite the complexity and higher capital cost of the technology which is employed, the plutonium breeder simply represents a sophisticated method of heating water with nuclear weapons material.

2. Breeder Primer

Many heavy atomic nuclei are capable of being fissioned; but only a fraction of these are fissile, that is, fissionable by slow (or zero energy) neutrons, as well as fast (highly energetic) neutrons. Only one fissile nuclide, uranium-235 (U-235), is found in nature in sufficient abundance to use as a nuclear fuel. It occurs with an isotopic abundance of 0.72 percent. The rest of natural uranium, except for traces of U-234, is non-fissile U-238. Most reactors today are fueled with uranium -- usually after it has been enriched to increase the concentration of U-235. The power reactors in Russia are primarily water-cooled graphite-moderated channel reactors (called "RBMKs"), or pressurized water [cooled and moderated] reactors (called "VVERs"). Both reactor types are currently fueled with low enriched uranium. The VVERs are also called Light Water Reactors (LWRs) because they are cooled with ordinary water. The water also serves to moderate, or slow down, the neutrons, thereby improving the probability of fissioning the U-235. In the RBMKs ordinary water is the coolant, but graphite is used as the neutron moderator.

If nuclear reactors were to be operated in large numbers for many years, U-235 would eventually become scarce, and the cost of uranium fuel could substantially increase. It is possible to manufacture alternative fissile isotopes from abundant non-fissile material by a process called conversion. The two most important fissile isotopes produced by conversion are U-233 and plutonium-239 (Pu-239). U-233 is produced from thorium-232, and Pu-239 from U-238, by neutron absorption.[3]

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[3] When U-238 captures a neutron not sufficiently energetic to cause fission, it transforms spontaneously to neptunium-239, which in turn transforms to Pu-239 in a relatively short time span.

Nuclear reactors can be very efficient converters because they can be designed to provide a copious supply of extra neutrons.

On average, fissioning atoms in reactor fuel each eject somewhat more than two neutrons, one of which is needed to sustain the chain reaction. Those neutrons not entering into fission reactions either leak from the reactor core or are captured in the fuel or by surrounding materials, including control rods. Typically in power reactors only a small fraction are lost or are captured in structural materials. Therefore on average close to one, and sometimes more than one, of the neutrons are captured in fertile materials, such as U-238. Uranium-fueled reactors (unless enriched to 100 percent U-235[4]) automatically produce Pu-239, since the fuel contains both U-235 and U-238. Before the spent fuel is removed from the reactor, some of the newly created Pu-239 atoms fission, just like the U-235, and some capture neutrons without fissioning. This latter process creates Pu-240, a heavier isotope of plutonium which is not fissile. Even heavier isotopes of plutonium are similarly created, e.g., Pu-241, which is fissile, from neutron capture by Pu-240, and Pu-242, which is not fissile, from neutron capture by Pu-241. At very low fuel burnup levels the fractional amounts of secondary plutonium isotopes are very small.[5] For a VVER at a fuel burnup level of 20,000 megawatt-days per metric ton (Mwd/MT), the fraction of Pu-240 is about 17 percent of the total plutonium, with the fraction of Pu-241 being approximately 11.5 percent, and that of Pu-242 about 4 percent (Figure 1). At higher burnups these fractional amounts increase so that at a burnup of about 40,000 Mwd/MT, the isotopic ratios are about:[6]

(Pu-239:Pu-240:Pu-241:Pu-242) = (0.55:0.21:0.15:0.7).

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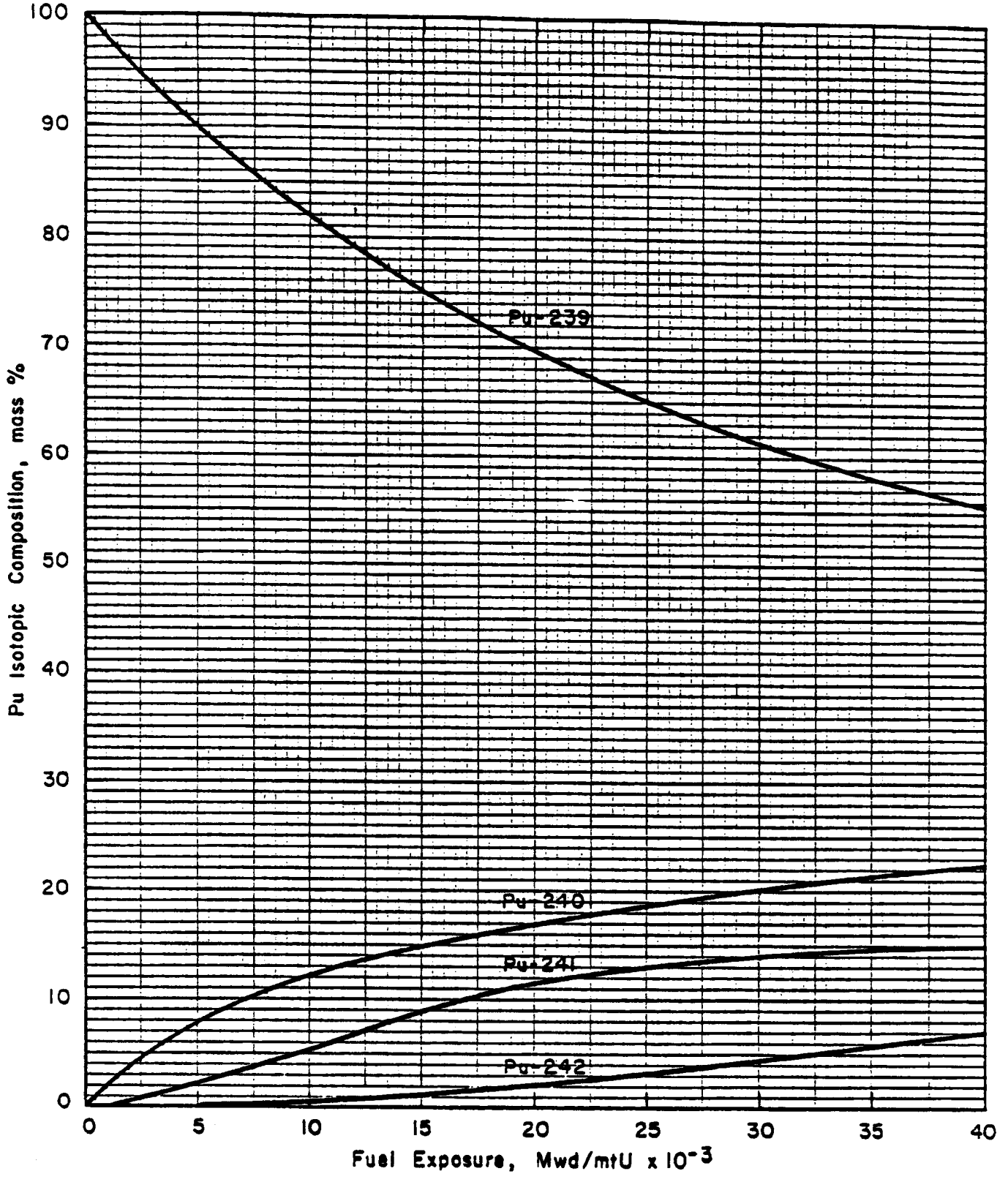
[4] Some reactors are fueled with uranium enriched close to this theoretical limit. U.S. naval reactors, for example, use uranium enriched to 97.3% U-235.

[5] Fuel burnup is a measure of the amount of fuel consumed and is a function of the reactor design, the power level and the length of time the fuel remains in the reactor. Burnup can be expressed as a percentage of the fuel consumed. Since the energy produced by the reactor is a function of the amount of fuel consumed, it is also common to express the burnup in terms of the megawatt-days of energy produced per metric ton of uranium in the reactor (Mwd/MT).

[6] See also, J. Carson Mark, *Reactor-Grade Plutonium's Explosive Properties*, Nuclear Control Institute, August 1990.

Figure 1: Plutonium isotopic composition as a function of fuel exposure in the reference PWR.



Plutonium with a Pu-240 content less then 7% is called weapon-grade plutonium; 7 to less than 19% Pu-240 is called fuel-grade; and plutonium with a Pu-240 content of 19% or greater is called reactor-grade plutonium.

A typical commercial-size VVER will consume about 1000 kilograms (kg) of fissionable material per year.[7] The conversion ratio, defined as the ratio of fissile atoms produced to fissile atoms consumed, is about 0.5 to 0.7 for an LWR fueled with low enriched uranium (3% - 5% U-235).[8] Assuming a conversion ratio of 0.6, then (0.6 x 239/235 =) 0.61 g of Pu-239 are produced for every g of U-235 consumed, or alternatively, (0.61 x 1.05 x 1.169 =) 0.75 g of Pu-239 are produced per Mwd.[9] Most of the Pu-239 is either fissioned, or converted to heavier isotopes, in situ.

Annually, a VVER fueled with uranium will discharge about 260 kg of plutonium (typically, 1.9% Pu-238, 57.9% Pu-239, 24.7% Pu-240, 11% Pu-241, and 4.4% Pu-242).[10] When operating with mixed plutonium-uranium oxide fuel (MOX), a mixture of recycled plutonium and natural uranium, after several refuelings the annual spent fuel discharge may contain as much as 550 kg of plutonium

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[7] Here, we assume the reactor capacity is 3000 Megawatt -thermal (Mw_t) (1000 Megawatt-electric (Mw_e) with a thermal efficiency of 33.3%), and its capacity factor is 0.75. (A capacity factor of 0.75 means the energy output of the reactor during a given period is the same as it would be if the reactor operated at 100% power for 75% of the time.) During one year it will produce (3000 x 365.25 x 0.75 =) 822,000 Mw-days (Mwd) of thermal energy. One Mwd is produced by the fission of 1.05 grams (g) of U-235, or 1.068 g of Pu-239. About 95% of the energy produced in a VVER comes from fission of U-235 and Pu-239, and the remaining 5% by fast neutron fission of U-238. Thus, 822,000 Mwd can be produced by fissioning 820-834 kg of U-235 and Pu-239, and 44 kg of U-238. In about 14.5% of the cases where U-235 captures a neutron, it does so without fissioning, resulting in the production of U-236. Consequently, 1.169 g of U-235 are consumed for every g fissioned.

[8] The conversion ratio varies with fuel enrichment and other reactor design parameters. For a reactor fueled with natural uranium the conversion factor is 0.894; see John R. Lamarsh, *Introduction to Nuclear Engineering*, (Reading, MA: Addison-Wesley Publishing Company, 1975), p. 110.

[9] One megawatt-day (Mwd) is produced per 1.05 g U-235 fissioned, and 1.169 g U-235 are consumed per g U-235 fissioned; ibid, p. 75.

[10] U.S. Nuclear Regulatory Commission, *Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors*, NUREG-002, Vol. 3, pp. IV C-70, C-75, and C-82. Values in these tables, which are for a boiling water reactor (BWR), have been reduced to reflect operating at a capacity factor of 0.75, rather than 0.8. For the same level of fuel burnup the VVER will discharge a slightly smaller amount of plutonium. The concentration of Pu-240 and Pu-242 will be smaller, with differences due primarily to the differences in fuel enrichment (1-2% higher enrichment in a VVER compared to a BWR).

(typically, 3.4% Pu-238, 41.7% Pu-239, 29.2% Pu-240, 15.2% Pu-241, and 10.4% Pu-242).[11]

By judicious choice of fuel and reactor design the conversion ratio can be increased to greater than one, thereby producing more fuel than is consumed. In this case the conversion ratio is called the "breeding ratio," and the reactor is called a "breeder." For neutron energies above about 0.1 million electron volts (MeV) - so-called "fast" neutrons - the average number of neutrons released in fission per neutron absorbed in U-235, U-233, and Pu-239 increases as the energy, or speed, of the neutron is increased. At neutron energies around 1 MeV the average number of neutrons released in fission per neutron absorbed by Pu-239 is 3 - compared to an average of 2.07 neutrons per fission per thermal neutron absorbed by uranium-235. Thus, a plutonium fueled reactor that is designed so as not to slow down, or moderate, the neutrons, offers the prospect of achieving a higher conversion ratio relative to other reactor designs. One can find in the literature fast breeder reactor (FBR) designs with breeding ratios in the range 1.3 to 1.44.[12] However, there is a tradeoff between the breeding ratio achieved and the safety of the design. More recent FBR designs offer breeding ratios in the range 1.0 to 1.3. We will have more to say about the plutonium inventories of breeders when we return to discuss the risks associated with the breeder's fuel cycle.

In order to avoid slowing down the neutrons, the fast breeder reactor fuel, or core, must be very compact. The tightly compacted core places greater demands on the coolant, which also should have a low moderating effect on the neutrons. To meet these two objectives, low neutron moderation and good heat conductivity, liquid sodium was chosen as the preferred coolant, hence the name "liquid metal fast breeder reactor."[13]

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[11] Ibid.

[12] U.S. Atomic Energy Commission, *Proposed Final Environmental Statement, Liquid Metal Fast Breeder Reactor Program*, WASH-1235, Vol. 2, December 1974, p. 4.2-170.

[13] There are also fast breeder designs that utilize helium as a coolant, the so-called Gas-Cooled Fast Breeder (GCFB).

3. Status of National Fast Breeder Development Efforts[14]

3.1 United States

The U.S. interest in breeder reactors dates back to the Manhattan Project days, when the possibility was first recognized by pioneers in the nuclear field. In 1945 the development of the plutonium-fueled fast breeder was established as a major goal of the Argonne National Laboratory (ANL) Division of the Manhattan District Metallurgical Laboratory. The 0.025 megawatt-thermal (Mw_t) mercury-cooled Los Alamos Fast Breeder ("Clementine") was used beginning in 1946 to demonstrate the feasibility of operating with fast neutrons, plutonium fuel and a liquid metal coolant. On December 24, 1952 the fuel cladding burst, releasing plutonium into the mercury coolant, and Clementine was permanently shut down. (See Table 1 for a summary of the history of FBR's by nation.)

The 1.2 Mw_t (0.2 megawatt-electric (Mw_e)) Experimental Breeder Reactor I (EBR-1) was built and operated by ANL from August 1951 through December 1963 to prove the breeding principle in a fast reactor and establish the engineering feasibility of using liquid metal coolant in power producing reactors. In 1951, EBR-I became the first nuclear reactor technology to generate electricity. EBR-I had a prompt positive power reactivity coefficient[15] due to fuel rod bowing, making it unstable under accident conditions. As the power of the reactor increased, the temperature gradient across the core caused the fuel rods to bow in toward the center of the reactor core. The more compact fuel arrangement added to the reactivity, causing the power to further increase. During an experiment at EBR-I on November 29, 1955, a reactor accident occurred resulting in a meltdown of the central region of the highly enriched uranium core. The core was rebuilt and the reactor operated successfully until it was decommissioned.

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[14] The developments through April 1988 are summarized in "Outlook On Breeders," *Nucleonics Week*, April 28, 1988.

[15] Reactivity is the fraction of neutrons born which are in excess of those required to hold the population constant. For an operating reactor, when the reactivity is zero the reactor power level stays the same. The term reactivity coefficient is used to designate the effect on reactivity caused by a small change in a specific operating variable. The power reactivity coefficient is defined as the change in reactivity resulting from a unit change in the power level. For a reactor to be stable, you do not want increases in the power level to cause changes in the reactor's physical condition, which in turn cause the reactivity, and therefore the power level, to increase further.

Table 1.
Fast Reactors by Nation

Nation	Name (proposed)	Location	Operator	Startup-Shutdown	Capacity MWt	MWe
USA						
	1. Clementine	LANL	USAEC	1946-1952	.025	-
	2. EBR-1	INEL	USAEC	1951-1963	1.2	0.2
	3. LAMPRE	LANL	USAEC	1961-1965	1	-
	4. EBR-2	INEL	USDOE	1963-	62.5	20
	5. Enrico Fermi-I	Monroe, MI	PRDC	1963-1971	200	65
	6. SEFOR	Arkansas	USDOE (a)	1969-1972	20	-
	7. FFTF	Hanford	USDOE	1980-	400	-
	8. (Clinch River BR)	(ORNL)	(USDOE-TVA)	CANCELLED	(975)	(350)
UK						
	1. Dounreay FR	Dounreay	AEA	1959-1977	60	13
	2. Prototype FR	Dounreay	AEA	1974-1994	600	254
France						
	1. Rapsodie	Cadarache	CEA	1967/1970-1982	20/40	-
	2. Phenix	Marcoule	CEA	1973-	567	250
	3. Super Phenix	Creys	GNR*	1985-	3000	1200
Germany						
	1. KNK-I/II	Leopoldshafen	Gk/V	1971/1977-	58	21
	2. SNR-300	Kalkar	SBKkG (b)	IS	736	327
USR						
	1. BR-1/2	Obninsk	SCUAE	1955/1956-1957	-/.2	-
	2. BR-5/10	Obninsk	SCUAE	1958/1973-	5/10	-/15
	3. BOR-60 Melekess	Dimitrovgrad	MAPI	1969-	60	12
	4. BN-350	Shevchenko	SCUAE	1972-	750	350 (c)
	5. BN-600	Beloyarsk	MAPI	1980-	1470	600
	6. (BN-800)	(Beloyarsk-4)	(MAPI)	CANCELLED		(800)
	7. (South Urals 1)	(Chelyabinsk-40)	(MAPI)	CANCELLED ?		(800)
	8. (South Urals 2)	(Chelyabinsk-40)	(MAPI)	CANCELLED		(800)
	9. (South Urals 3)	(Chelyabinsk-40)	(MAPI)	CANCELLED		(800)
Japan						
	1. Joyo	Oarai	PRNFDC	1977/1983-	75/100	-
	2. Monju	Tsuruga	PRNFDC	1993	714	280
India						
	1. FBTR	Kalpakkam	DAE	1967	42	15

Notes:

a. Sponsors included Germany's KNL, Euratom, and the Southwest Atomic Energy Association.
b. With Belgium and the Netherlands participating.
c. Includes 150 MWe for desalination.

Compiled by the Natural Resources Defense Council

The 1 Mw_t Los Alamos Molten Plutonium Reactor Experiment (LAMPRE) experimental fast reactor operated at Los Alamos for about four years beginning in 1961. It was the first reactor to use a fuel designed to be liquid under operating conditions. The 62.5 Mw_t EBR-II pool-type research reactor went critical[16] in 1963. It is still operating today as a test facility for a new fuel cycle concept which goes by the name Integral Fast Reactor (IFR) technology. We will discuss the merits of this technology at the end of this paper.

The 200 Mw_t (65 Mw_e) Enrico Fermi I reactor, located in Monroe, Michigan, was the first LMFBR demonstration plant. It was built and operated by the Power Reactor Development Company (PRDC), a utility consortium. On October 5, 1966, during a controlled, slow increase in power, a sodium flow blockage resulted in a fuel melting in two subassemblies of the reactor core. This accident scenario had not been considered credible until that time.

The 20 Mw_t Southwest Experimental Fast Oxide Reactor (SEFOR) was constructed in the mid-1960s with the purpose of conducting research on the safety of the LMFBR. It began operation in 1969, and was shut down in 1972 after fulfilling its mission.

In 1967 the U.S. Atomic Energy Commission (USAEC) selected the LMFBR over other breeder concepts and made it the highest priority civilian reactor development effort. After the failure of Fermi I the USAEC decided to develop a fuel and materials test facility before constructing a larger demonstration plant. After several years of construction delay, the 400 Mw_t Fast Flux Test Facility (FFTF) went critical in 1980. A loop-type[17] fast reactor, FFTF also served as a one-third scale predecessor to the Clinch River Breeder Reactor (CRBR) demonstration plant. Lacking a radial blanket of U-238, the FFTF was not designed to breed. FFTF is still operating today.

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[16] When the fission reaction proceeds at a constant rate the reactor is said to be critical. Simply stated, "went critical" means "was turned on."

[17] In a loop design the intermediate heat exchangers are outside the reactor vessel and connected to it by sodium pipes (or "loops"); in a "pot" or "pool" design the intermediate heat exchangers are inside a larger reactor vessel ("pot") containing a larger inventory (or "pool") of sodium. See section 3.3 for a discussion of pool- vs. loop-type reactors.

The 975 MW_t (350 Mw_e) CRBR project was launched in 1971. On June 4 of that year, then President Richard Nixon said "[o]ur best hope for meeting the Nation's growing demand for economical clean energy lies with the fast breeder reactor."[18] In the early 1970s this technology was the largest energy research and development program in the United States. By the mid-1970s it had become apparent that the breeder was not economical and was inconsistent with U.S. nuclear nonproliferation objectives. President Carter tried to cancel the CRBR. He suspended the licensing process, but was never able to convince the Congress to withdraw funding. Shortly after he took office President Reagan renewed the CRBR licensing process. However, before a Construction Permit was granted a coalition of environmentalists and fiscal conservatives convinced the Congress in 1983 to withdraw funding for CRBR, thus killing the project.

With cancellation of the CRBR, the U.S. breeder development program was curtailed. Fuel research continued at the FFTF and EBR-II. Continued operation of the FFTF is now being challenged in the Congress annually and its days are numbered. The U.S. Department of Energy (DOE) funded two competing design concepts for an Advanced Liquid Metal Reactor (ALMR). With Congress having been convinced that breeders were unnecessary, the word "breeder" was dropped by the program. The Power Reactor, Innovative Small Module (PRISM), originated by General Electric in 1981, was selected by DOE in 1988 as the reference ALMR design concept for further government subsidized development.[19]

PRISM utilizes nine reactor modules arranged in three identical 415 Mw_e power blocks for an overall plant net rating of 3825 Mw_t (1245 Mw_e). The reference fuel for PRISM is a heterogeneous metal alloy fuel being developed by Argonne National Laboratory (ANL) and tested at EBR-II; Mixed Plutonium-Uranium Oxide (MOX) fuel is an alternate. For the reference case, fuel recycling facilities are

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[18] Press release, The White House, Office of the White House Press Secretary, June 4, 1971.

[19] General Electric is working with an industrial team consisting of Bechtel Power Corporation, Borg Warner, Foster Wheeler, and United Engineers and Constructors on the design of PRISM. In addition, research and development work supporting the PRISM design is being performed by Argonne National Laboratory, the Energy Technology Engineering Center, Hanford Engineering Development Laboratory, and Oak Ridge National Laboratory. The conceptual design report for PRISM was submitted to the NRC on November 14, 1986, and NRC published a draft pre-application Safety Evaluation Report for PRISM in September 1989 (Source: MHB Technical Associates, *Advanced Reactor Study*, Prepared for Union of Concerned Scientists, July 1990, p. 2-37.)

collocated at the reactor plant site, and the fuel cycle concept goes by the name Integral Fast Reactor (IFR) technology. We will return to PRISM and the IFR fuel cycle at the end of this paper when we discuss their respective merits.

Over the last three decades the United States has spent about $16,000 million on breeder reactor technology.[20] With government funding only for design studies and experimental research at EBR-II and FFTF, the U.S. breeder program is struggling to survive.

3.2 United Kingdom

The U.K. became involved in FBRs early in its nuclear program. Its 60 Mw_t (13 Mw_e) Dounreay Fast Reactor (DFR) went into operation in 1959, and in 1962 became the first FBR to generate on a national electric grid. DFR was shut down in 1977, three years after its successor, the 560 Mw_t (250 Mw_e) prototype fast reactor (PFR), went on line in Dounreay. PFR has successfully operated as a fast reactor fuel test facility. A number of small leaks in welds have kept power levels and load factors down, and all three superheaters and reheaters in the secondary cooling circuit had to be replaced in 1987. In July 1988, the government decided that it would stop funding operations at PFR in March 1994, and its associated reprocessing plant in 1997.[21]

The U.K. at one time planned to build its own 1320 Mw_e Commercial Demonstration Fast Reactor (CDFR), but it was never funded. The U.K. government subsequently spearheaded an effort to develop a EFR (European Fast Reactor), only to conclude in 1988 that there was no justification for the U.K.'s investing 800 million pounds ($1,360 million) in the EFR "knowing that there [is] not likely to be a commercial customer for the technology for decades."[22] The House of Commons' Select Committee on Energy recommended in July 1990 that the U.K. withdraw from EFR collaboration in 1997 at the latest "if no new evidence has become available indicating that there is a likelihood of fast reactors becoming viable by about 2020-2030." In response, the government has decided

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[20] U.S. Congress, Office of Technology Assessment, *Energy Technology Choices: Shaping our Future*, OTA-E-493, July 1991, p. 83.

[21] *Nucleonics Week*, December 13, 1990, p. 14.

[22] Ibid.

that it will review its current participation in the EFR project in 1993 and again in 1997.[23]

3.3 France

The 40 Mw_t Rapsodie reactor at Cadarache began operation in 1967, marking France's entry into the breeder race. Rapsodie was shut down permanently in 1982 after cracks were found in reactor vessel nozzles. The 567 Mw_t (250 Mw_e) Phenix pool-type reactor[24] at Marcoule went on line in 1973, a year ahead of PFP in the U.K. It was followed by the 3000 Mw_t (1240 Mw_e) Superphenix (also a pool design) at Creys-Malville, which went critical in 1983 and became operational in September 1985. With start-up of Superphenix, the French assumed the lead in the international race to develop the breeder. The French had grand plans to quickly follow with the construction of several 1,500 Mw_e plants, called RNR-1500, or Superphenix-2. But French nuclear industry hopes for a robust breeder reactor economy were dashed when the bills came in. The capital cost of Superphenix turned out to be about 2.5 times higher than a comparable pressurized water reactor (PWR) built in France.[25] Subsequent cost estimates of the RNR-1500 by Novatome promised a FBR/LWR cost ratio of 1.7-1.8.[26] The Novatome study also concluded that with series production of 12 Superphenix units, the cost ratio could be brought down further, but not below 1.5.[27] Costs 50% higher than LWRs are unacceptable to the utilities, and France's Commissariat a l'Energie Atomique (CEA) has concluded that sufficient capital cost reductions probably cannot be achieved with current designs, no matter how they are improved.[28]

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[23] Ibid.

[24] See discussion later in this section comparing pool-type and loop-type reactors.

[25] *Nucleonics Week*, April 28, 1988, p. 3.

[26] Ibid. See also Adrien Mergui, "Commissioning the World's First Commercial Scale FBR at Creys-Malville," *Nuclear Engineering International*, May 1988, pp. 20-24; and "What Future is There for Superphenix?," ibid, December 1990, p. 12.

[27] *Nucleonics Week*, April 28, 1988, p. 4.

[28] Ibid.

Unlike the U.S. breeder program, when designing Phenix and Superphenix the French opted for a pool rather than a loop design.[29] In the pool design the intermediate heat exchangers are inside the reactor vessel, whereas in the loop they are outside. The pool has construction cost advantages over the loop, but maintenance can be a nightmare. Both Phenix and Superphenix have been plagued by problems related to use of sodium as a coolant. In both August and September of 1989, Phenix experienced a series of reactivity drops. It was hypothesized these were due to entrainment of an argon bubble of about 30-50 liters by sodium pump currents through the Phenix core periphery. Phenix's gas purge assemblies and operating procedures were modified, and it was permitted to restart on December 27, 1989. However, the reactivity problem recurred nine months later, in September 1990. This time the reactivity fluctuation was so large that experts, noting the bubble would have to be hundreds of liters, doubted that it was caused by argon bubble entrainment. Operators of Phenix now hypothesize the reactivity fluctuations were due to instrumentation faults. In the absence of sufficient data to prove any hypothesis, the French nuclear safety authority (DSIN) has refused to permit Phenix to restart.[30]

Superphenix has been plagued by sodium leaks associated with its steam generators and has been shut down for extended maintenance periods.[31] It has not operated since July 1990, and its capacity factor is so low it would not be competitive even if its construction cost was on par with the PWR. In May 1991, the Conseil d'Etat, France's supreme administrative court, annulled the legal basis for the Superphenix operating authorization.[32] Also, DSIN concluded the reactivity problem at Phenix must be understood before Superphenix can restart. The French government is now threatening to shut down Superphenix

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[29] See footnote 13.

[30] *Nuclear News*, August 1991, pp. 92-93.

[31] Superphenix was shutdown May 26, 1987; *Nucleonics Week*, February 11, 1988, p. 9.

[32] *Nucleonics Week*, May 30, 1991, pp. 5-6. The Superphenix's original 1977 nuclear construction/operation license (Decret d'Autorisation de Creation, or DAC) allowed operation with a fuel transfer-storage drum. The drum failed and was modified limiting its use to transfer, but not storage. The government authorized restart of the reactor on January 10, 1989. Swiss and French intervenors argued before the court that this restart authorization was unlawful in that it precluded the opportunity for public inquiry. See also, *Nucleonics Week*, May 23, 1991, pp. 1 and 12.

permanently.[33] In oral remarks, Dominique Strauss-Kahn, French Minister for Industry and Energy, told legislators in June of this year that France is abandoning fast breeder reactor development, but his remarks were later amended to say that "no decision has been taken."[34]

3.4 Germany

The West German government began breeder development in 1956.[35] The 58 Mw_t (21 Mw_e) KNK research reactor went on line in 1971 at the Karlsruhe Nuclear Research Center (KFK). KNK was rebuilt as KNK-2 to test FBR fuel and went on line in 1977. The next FBR development was the 736 Mw_t (327 Mw_e) SNR-300 loop-type demonstration plant at Kalkar, started in 1972 with an initial cost projection of DM 1,500 million ($900 million). By mid-1988, Schnell-Brueter-Kernkraftwerksgesellschaft mbH (SBK), the quadrilateral European consortium of owners,[36] had spent DM 7,000 million ($4,800 million), eight times the original cost, on the project.[37] At that point the principal owner, REW, no longer had any commercial interest in operating the reactor.[38]

Whether Kalkar was safe to operate was the subject of heated debates between the state government of North Rhine-Westphalia (NRW), run by the Social Democratic Party (SPD), and the federal government in Bonn. Claiming Kalkar had a large positive reactivity coefficient; a high potential for exothermic chemical reactions that could lead to sodium-concrete interactions, sodium fires and gas explosions; a weak secondary containment; and lack of separation of the redundant electrical systems, for the past three years NRW has refused to license

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[33] "France may shut down Superphenix permanently," *Energy Economist*, August 24, 1990, p. 1.

[34] *Nucleonics Week*, July 11, 1991, p. 1.

[35] *Nucleonics Week*, April 28, 1988, p. 11.

[36] Consisting of Rheinisch-Westfaelisches Elektrizitaetswerk AG (RWE) (68.85%, N.V. Samenwerkende Elektricitetis-Produktiebedrijven (SEP) in the Netherlands (14.75%), S.A. Electronucleaire N.V. in Belgium (originally 14.75%, then reduced to 8%), and the Central Electricity Generating Board (CEGB) in the U.K. (1.65%).

[37] *Nucleonics Week*, April 28, 1988, p. 11.

[38] Ibid.

its operation in defiance of an order from West Germany's Federal Constitutional Court.[39]

Although fully constructed, the Kalkar plant will probably never be operated. It has been costing about DM 100 million ($69 million) per year to maintain the cold reactor for the past three years; and it will cost an estimated DM 350 ($242 million) to dismantle it.[40] Its owners and operators are seeking buyers for its components. AEA Technology, in hopes of keeping the British PFR alive after March 31, 1994, has been discussing with Kalkar's owners and operator the possibility of transferring Kalkar fuel to use in PFR.[41]

3.5 Consolidated European Efforts

In 1972 a tripartite effort by French, German and Italian Electric utilities had grandiose plans to build a 5000 Mw_t (2000 Mw_e) SNR 2000, to become operational in 1983, but the demise of Kalkar killed this idea as well.

More recently, with national programs stalled, European efforts have merged into a program to design the EFR (European Fast Reactor), but no date has been set for a decision on construction.[42] Because of the high cost of breeders EFR is likely to remain a paper study.

3.6 Russia/Soviet Union

The Soviet Union was one of the earliest supporters of fast breeder technology. The 10 Mw_t BR-10 at Obninsk began life as the 0.2 Mw_t BR-2 in 1956. The 60 Mw_t BOR-60 test facility at the Dimitrovgrad began operating in 1959. It was followed by the 750 Mw_t BN-350 loop-type fast reactor, which began operating in 1972 at Shevchenko on the Caspian Sea to desalinate water and produce power. In February 1975 BN-350 suffered a major setback with a sodium-water interaction involving 800 kg of sodium and resulting in a two-hour fire.[43] (See Section 4.1

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[39] Ibid. and *Nucleonics Week*, May 31, 1990, pp. 2-3.

[40] *Nucleonics Week*, December 20, 1990, p.3.

[41] *Nucleonics Week*, January 24, 1991., p. 8.

[42] "Reviewing Progress on the European Fast Reactor, " ibid., August 1990, pp. 39-44.

[43] *Nucleonics Week*, April 28, 1988, p. 14.

for a discussion of sodium's reactive properties.) After repair of five steam generators and replacement of the sixth, BN-350 operated at 650-700 Mw_t (up to 130 Mw_e) while producing 80,000 MT of water a day for the city of Shevchenko.

The 1470 Mw_t (600 Mw_e) BN-600 pool-type demonstration plant at Beloyarsk, an hour north of Sverdlosk in the central Urals, began operating in 1980 as the world's first commercial-size fast reactor. Early problems with leaking fuel, and steam generator leaks due to faulty welds, were overcome; for the last ten years BN-600 has operated at a 66 percent capacity factor.[44] BN-600 turned out to be 1.5 to 1.7 times as expensive to construct as a 1000 Mw_e VVER.[45] Thus, fast breeders turned out to be just as uneconomical in Russia as they have been in the West.

In the past, BN-350 and BN-600 have been fueled with highly enriched uranium (HEU) rather than plutonium, probably to conserve the plutonium for possible military use.[46] Only the small BOR-60 fast reactor in Dimitrovgrad has been operating with MOX fuel.[47] The use of HEU instead of plutonium lowers the breeding ratio to below one, which means BN-350 and BN-600 are not being operated as breeders.

The Ministry of Medium Machine Building (now the Russian Ministry of Atomic Energy) had planned to follow BN-600 with four 800 Mw_e BN-800 units, one at Beloyarsk and three collocated at the Mayak Chemical Combine (Chelyabinsk-65). Preliminary work began at Beloyarsk in 1986, but the workers were reassigned elsewhere in 1989.[48] The project was one of those frozen by Moscow authorities due to lack of funds. The three breeder unit South Urals Nuclear Generating Station was possibly meant to co-produce electricity and plutonium for weapons, replacing the aging graphite-moderated plutonium production reactors at the site.

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[44] *Nucleonics Week*, July 26, 1990, p. 13.

[45] Ibid., p. 15. BN-600 cost 550 rubles per installed kw compared to 333 rubles/kw for the 1000 Mw_e VVER; *Nucleonics Week*, July 26, 1990, p. 14.

[46] In the Soviet Union the Ministry of Atomic Power and Industry (MAPI), formerly the Ministry of Medium Machine Building, has been responsible for the nuclear weapons program, the military and civil reactor fuel cycles, and breeder development.

[47] Ibid.

[48] *Nucleonics Week*, July 26, 1990, p. 14.

The latter were recently shut down due to the surplus of weapon-grade plutonium already on hand.

Construction of the three unit BN-800 South Urals project began in 1984. Site work on at least two of the reactors was started, but in 1989 the project was scaled back to one unit in the face of local public opposition, and no doubt for lack of funds as well. The opposition followed the Chernobyl accident, after which the Supreme Soviet forced Chelyabinsk-65 site managers to reveal details of the extensive radioactive contamination on and around the site due to 40 years of mismanagement of high level nuclear waste. Through the end of 1989 some 270 million rubles had been spent on the project.

Seeking alternative employment for the production reactor workers at the Chelyabinsk-65 site, and in the hopes of marketing breeders abroad, Mayak and the Ministry of Atomic Energy continue to support construction of at least one BN-800 reactor. Mayak officials are also arguing that Although some work on the concrete foundation has been completed, no significant construction appears to have taken place since about 1987.

Although one-third larger than BN-600, the BN-800 did not benefit from economies of scale. The new breeder was estimated to cost 900 rubles/kw compared to 600-650 rubles/kw for the improved-safety VVER.[49]

3.7 Japan

The Japanese government and its Power Reactor & Nuclear Fuel Development Corp. (PNC) began fast breeder development in 1967. Through 1986, Japan pumped 563,000 million yen (U.S. $4,510 million) into the fast breeder effort. Japan's first FBR reactor was the 75 Mw_t Joyo (Eternal Sun) which started up in 1977 and was boosted to 100 Mw_t in 1983.[50] Construction of the 714 Mw_t (280 Mw_e) Monju (Buddha's Wisdom) demonstration LMFBR was begun in October, 1985. Monju is located in the Wakasa region on the Sea of Japan, 65 kilometers from Kyoto. Having cost six hundred thousand million yen ($4,300 million) on

[48] *Nucleonics Week*, July 26, 1990, p. 14.

[50] *Nucleonics Week*, Apr 28, 1988, p. 14.

construction (which took over six years),[51] While Monju is scheduled to reach criticality in October 1992, it is unlikely to begin operation before next year.

Japan Atomic Power Co. (JAPC) has begun conceptual design studies of a 600 to 800 Mw_e Demonstration Fast Breeder Reactor (DFBR).[52] The concept will be based on the loop-type design despite the construction cost advantages offered by the pool-type reactor.[53] Japan's Atomic Energy Commission (JAEC) has also initiated a research and development effort designed to evaluate nuclide partitioning and transmutation by irradiation in fast reactors, including a demonstration of the transmutation concept in Joyo and Monju.[54]

Japan was planning to have a commercial breeder by 2010, but JAEC now projects that commercial reactors will start operating around 2020-2030.[55] In April 1992, Takao Ishiwatari, president of PNC and a top nuclear expert in the government, has sparked a new debate over Japan's breeder program by expressing his fear that it would lead to the proliferation of toxic plutonium and saying "it would be better for Japan to develop a [power generating] system that burns up plutonium rather than one that breeds it."[56]

3.8 India

India constructed a 40 Mw_t (15 Mw_e) Fast Breeder Test Reactor (FBTR) at Kalpakkam, near Madras on the Bay of Bengal, based on the design of France's Rapsodie experimental fast reactor. The FBTR went critical in October 1985. A series of problems kept FBTR off line for much of the time between 1985 and 1988.[57]

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[51] *Nucleonics Week*, November 3, 1988, p. 3.

[52] *Nucleonics Week*, July 19, 1990, pp. 4-6.

[53] *Nucleonics Week*, July 19, 1990, pp. 4-6.

[54] *NuclearFuel*, December 12, 1988, p. 10.

[55] *Nucleonics Week*, October 4, 1990, p. 8; and *Nature*, July 4, 1991, p. 4.

[56] *The Washington Post*, April 22, 1992, p. A24.

[57] *Nucleonics Week*, April 28, 1988, pp. 12-13.

India plans to break ground for a 500 Mw_e prototype fast breeder reactor (PFBR), based on the pool design, around the year 2000.[58] It is also to be located at Kalpakkam.

The plutonium for the nuclear device exploded by India in May 1974 was obtained from its CIRUS research reactor and recovered at the Trombay reprocessing plant that was established as part of India's civil breeder program. P.K. Iyengar, chairman of India's AEC, played a leading role in developing India's 1974 nuclear weapon test. Thus, India's breeder program appears to have had both a civil and a military component.

3.9 Brazil and Argentina

These two Latin American countries announced a joint fast breeder development program in November 1988. Plans are to develop a small fast breeder and bring it on-line by the year 2005, with Argentina providing the plutonium from its Ezeiza reprocessing plant and Brazil supplying the sodium moderator.[59]

4. Risks of Plutonium Utilization with the Fast Breeder Reactor

Economics is not the only, nor the most important, issue associated with breeders. Development of a plutonium breeder economy carries enormous societal risks. Russia's potential reliance on an energy supply technology based on nuclear-weapons-usable material is cause for profound concern, not just in Russia, but throughout the world.

There are two categories of risks associated with fast breeders that differ significantly from those associated with the conventional reactors operating with low enriched uranium fuel, namely, those associated with operation of the reactor itself, and those associated with reliance on weapons-usable material as fuel.

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[58] Ibid.

[59] *Nucleonics Week*, April 6, 1989, p. 10.

4.1 Reactor Safety Issues

Any event that leads to substantial loss of integrity of the reactor core geometry is called a core disruptive accident (CDA).[60] In a fast breeder this could be an explosion, a non-energetic melt-down of the core, or a melting of a small part of the core. The energetic CDA is sometimes referred to as a Bethe-Tait event, named after the two American authors, Bethe and Tait, who first attempted to model the magnitude of the ensuing explosive energy release. There are two broad categories of initiating events that can lead to a CDA: (1) a combination of a loss of coolant flow with failure to scram the reactor; and (2) a combination of an over-power transient (where too much reactivity is introduced into the reactor causing the power level to shoot up) with failure to scram (i.e., automatically insert the control or safety rods and terminate the chain reaction). In effect, with a fast breeder, serious trouble can result from either losing adequate cooling capacity without reducing the power level, or increasing the power without increasing the cooling capacity.

The first category of events could be initiated by a loss of power to the main circulation pumps and a failure of auxiliary power to restart these or any backup pumps. There could also be massive blockage in the coolant flow system, or a major pipe break in a loop-type design. These are not hypothetical initiating events. On August 13, 1991, Nine Mile Point Unit 2, an American LWR, experienced a station blackout and all backup power sources failed to operate. Also, recall that Fermi I experienced fuel melting due to sodium flow blockage.

Some fast reactors, including most pool designs, are configured so that even if there is total loss of power to the pumps, the natural circulation of the sodium will provide adequate decay heat removal and preserve core integrity, provided the reactor is immediately scrammed. Of course, no fast reactor can survive core damage if a common mode failure, e.g., an earthquake, destroys the pumps and prevents insertion of the control and safety rods.

An over-power transient could be triggered by an earthquake, or mismanagement of the control and safety systems such as occurred at Chernobyl Unit 4. The

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[60] Some breeder enthusiast, not wishing to acknowledge that such events are credible refer to them as Hypothetical Core Disruptive Accidents (HCDAs).

Phenix reactor is now shut down because of positive reactivity fluctuations that have not been satisfactorily explained.

Both loss-of-flow and over-power transient initiators can lead to cladding melting, and in the more severe cases, fuel melting. This may or may not lead to an energetic core disruption (a euphemism for an explosion), depending on how the fuel subsequently moves in the core.

To appreciate the possible consequences we will trace a progression of a hypothetical loss of flow event which could lead to an explosion. First, power is lost to the pumps, and we must also assume the redundant safety control systems fail to scram the reactor. In the hottest area of the core, which is near the center, sodium boiling begins. Because of plutonium's higher fission cross section at higher neutron energies, when boiling occurs and bubbles are formed in the coolant, there is less moderation of the neutrons. Consequently, the chain reaction rate increases. The reactor is said to have a positive reactivity coefficient due to loss of coolant.[61] The increase in power causes the rate of boiling to increase, which adds more reactivity, and so on. Almost immediately after boiling, the cladding begins to melt and the molten cladding is swept up the channel between the tightly bundled fuel rods. Fuel melting immediately follows and the molten fuel is swept in the same direction. As the cladding and fuel reach the colder blanket areas they refreeze, clogging up the sodium flow path within the fuel bundles. More melting occurs and with the flow path becoming increasingly clogged, the cladding and fuel begin to fall to the bottom of the core, clogging that area as well. Should the fuel mass at the top of the reactor core fall to the bottom under the force of gravity, recriticality of the fuel could occur. However, the energy released probably would not be enough to breech the seal between the reactor head and the reactor vessel.

A major unresolved issue is whether, and under what circumstances, an energetic interaction between the molten fuel (or cladding) and the sodium could take place.

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[61] Thermal reactors need the coolant to moderate the neutrons. Loss of coolant in an LWR shuts down the chain reaction. Loss of coolant in a fast reactor speeds up the chain reaction - a much more dangerous situation. One of the design flaws of the Chernobyl reactor was the fact that it had a positive reactivity coefficient with respect to the initial insertion of the control rods. When the operators wanted to shut the chain reaction down by inserting the control rods, they actually increased the reaction. The Chernobyl reactor exploded as a result.

When molten steel or aluminum is dropped into water the rapid transfer of the heat from the metal to water causes a steam explosion. The potential for molten cladding- and molten fuel-coolant interactions offers mechanisms for driving two subcritical masses of fuel together at speeds greater than those which would occur if one of the masses were accelerated by gravity alone. With the center of the core melted away, one worries whether the fuel now trapped at the top of the core could be explosively driven down against the fuel debris at the bottom of the vessel, all of this perhaps constrained within the intact cooler blanket rods around the circumference of the interior core. The resulting recriticality event is qualitatively similar to the gun assembly technique used in the atomic bomb dropped on Hiroshima. The explosive energy released under such a scenario would not be anything like an atomic bomb, but the resulting pressure pulse caused by a mass of sodium slamming against the reactor head could potentially rupture the seal between the reactor vessel and reactor head, providing a direct path for the release of sodium, plutonium fuel, and fission products into the secondary containment. The reactor closure head of the CRBR was designed to accommodate 660 megajoules (MJ) of energy released[62] - resulting in 75 MJ of upward kinetic energy of a sodium slug impacting the head - without breaking the seal between the reactor head and vessel.[63]

Even if the CDA is non-energetic, that is, the core melts and slumps to the bottom of the reactor vessel, melt-through of the reactor vessel can be anticipated within 24 hours. The melt-through of the reactor vessel, or the rupture of the reactor head seal, provides an avenue for subsequent sodium fires which ultimately will challenge the integrity of the secondary containment.

Sodium interacts exothermically on contact with air, water and concrete. When released as an aerosol in air, the combustion can be explosive. On contact with concrete, hydrogen is released, which in turn can burn or accumulate to a concentration that is explosive. Thus, sodium creates a serious safety risk unique

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[62] The explosion of one pound of TNT will release about 2 MJ of energy.

[63] U.S. Nuclear Regulatory Commission, *Safety Evaluation Report Related to the Construction of the Clinch River Breeder Reactor*, NUREG-0968, Vol. 2, Appendix A, March 1983, p. A.2-11. The NRC Staff analysis indicated that approximately 2550 MJ would be required to produce a slug impact kinetic energy close to the design capability of 275 MJ; ibid., p. A.2-10.

to the LMFBR. Typical of a large pool-type fast reactor, the Superphenix operates with 3,500 MT of sodium in the primary circuit.[64]

Typically the reactor vessel is housed in a concrete cell or cavity which is lined with steel. The cavity is sealed and filled with an inert gas such as argon. But if fuel melting is sufficient to melt through the reactor vessel, the much thinner liner is unlikely to remain intact. The very hot sodium will begin interacting with the concrete, generating additional heat and producing hydrogen gas. In the analysis of the CRBR CDA, it was estimated that the sodium could eat through the concrete at an initial rate of 18 cm per hour, slowing down as the sodium cools, and reaching a depth of about 75 cm before the sodium boils dry. The thermal degradation of the concrete caused by the molten core debris would double this penetration depth during the sodium boil-dry period and subsequent melt penetration could reach 5 to 8 meters (m).[65]

Soon after the sodium and molten mass of core debris begin attacking the concrete, the generation of heat and buildup of gas in the cavity would rupture the cavity seal and provide a direct path to the secondary containment. The secondary containment would not have the strength to contain the pressure increase caused by the resulting buildup. Moreover, there is the added risk of a sodium and/or hydrogen fire. All but the smallest fast breeders are likely to be designed with vents in the secondary containment. The reactor operator would have to open the vent to relieve pressure in the secondary containment to prevent catastrophic rupture of the containment. In the safety assessments of the CRBR, venting was assumed to occur between 10 and 36 hours after the initiation of the CDA.[66]

Of course, proponents of fast breeder reactors claim they are safe. They say that redundant control and safety systems will prevent a loss of flow or over-power

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[64] *Nucleonics Week*, December 13, 1990, p. 4. The smaller Kalkar and PFR reactors, both loop designs, have 548 MT and 900 MT of primary sodium, respectively; Nuclear Engineering International, *World Nuclear Industry Handbook*, 1991, p. 126.

[65] U.S. Nuclear Regulatory Commission, *Safety Evaluation Report related to the construction of the Clinch River Breeder Reactor*, NUREG-0968, Vol. 2, Appendix A, March 1983, pp. A.4-4 to A.4-8.

[66] Ibid., p. A. 5-10.

transient accident. These are familiar arguments that have been dispelled by the accidents at Three Mile Island and Chernobyl. Once you assume that fuel or cladding melting can occur, then the breeder enthusiasts are on very shaky ground, because they cannot accurately model the subsequent course of events using computers. Computer modeling of fuel and cladding movement, and their interaction with sodium coolant, following the loss of geometric integrity of the reactor core borders on witchcraft. The possible scenarios from this point to the end game are infinite. Many simplifying assumptions have to be made. There are so many variables and assumptions that an analyst can manipulate the calculations to predict any size energy release - anything from a partial core melt as occurred in the Fermi I reactor to a catastrophic explosion rupturing the integrity of the reactor vessel.

When the CRBR was canceled by the U.S. Congress it was undergoing a construction permit licensing review by the Nuclear Regulatory Commission (NRC). The applicant and the NRC staff each utilized a battery of analysts to assess the magnitude of potential loss of flow and over-power transient accident scenarios. The applicant's analysts chose parameters and simplifying assumptions leading to predictions of no energy releases or low-level energy releases which would not challenge the containment. The staff analysts made more conservative assumptions resulting in greater energy releases, but were always careful not to predict any consequences that would challenge the licensibility of the plant. The goal appears to have been to force the applicant to make small improvements in the safety of the CRBR design, without threatening the viability of the enterprise. Small changes to one or two assumptions would have led to model predictions that could challenge the containment.

Following the TMI accident, and the recognition that U.S. utilities were unlikely to order additional nuclear plants without radical improvements in reactor safety, the nuclear vendors initiated competing designs with improved safety. They often erroneously claimed that these designs were "inherently safe." One entry into the field was General Electric's PRISM design. As noted earlier, PRISM utilizes nine reactor modules arranged in three identical 415 Mw_e power blocks for an overall plant net electrical rating of 1245 Mw_e. Thus, each of the nine reactor modules has about one-fifth the power output of a BN-800.

PRISM, like other advanced "paper designs," appears safer than existing and previous designs such as the CRBR, Kalkar, Monju and Superphenix. The PRISM modules are relatively small pool-type reactors. Their size enables them to rely on several assertedly "passive" systems to perform essential safety functions. For example, PRISM is advertised as having "passive shutdown heat removal for loss-of-coolant events, and passive reactivity control for undercooling or overpower events with failure to scram."[67] The passive reactivity control is a negative reactivity feedback mechanism which causes the power level to decrease when the fuel heats up without input from control systems or operator action. This is referred to by some as "inherent shutdown," but the reactor does not actually go subcritical. Rather, the chain reaction keeps going, but at a much reduced power level.[68] The PRISM design is subject to large positive reactivity insertions in the event of sodium coolant boiling.[69] As noted above, large reactivity insertions can result in the destruction of the reactor, similar to what occurred in the 1986 Chernobyl Unit 4 accident.

Improvements in reactor safety as represented, for example, by the PRISM design, are not cheap. For the same power output, the large number of small reactor modules with duplicative control and safety systems should be more expensive than the more conventional LMFBR designs which are already uneconomical. Also the ability to efficiently breed fuel is lost. The time required to double the fissile plutonium inventory (i.e., the fuel doubling time) advertised for the reference fuel cycle for PRISM is 60 years. This is probably an optimistic value that would further erode under real operating conditions. The developers of PRISM hope to offset the higher costs of the modular design by eliminating safety systems, including the secondary containment, and by arguing that factory manufacture will bring economies of scale. This last argument was used previously in claims that breeders would eventually be competitive with LWRs -- claims that were never materialized.

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[67] L.N. Salerno, et al., "PRISM Concept, Modular LMR Reactors," *Nuclear Engineering and Design*, 109 (1988), pp. 79-86.

[68] MHB Technical Associates, *Advanced Reactor Study*, Prepared for Union of Concerned Scientists, July 1990, pp. 2-47 to 2-48.

[69] Ibid., p. 3-56

4.2 Risks associated with the Fast Reactor Fuel Cycle

The greatest danger associated with the plutonium fueled fast breeder lies with its fuel cycle. The advantages of breeding fuel in a fast reactor can only be realized if the plutonium is separated and used to make fresh fuel. The risks associated with the fast breeder fuel cycle are qualitatively the same as those associated with closing the LWR fuel cycle, reprocessing LWR spent fuel to recover plutonium for reuse in LWRs.

4.2a Plutonium Requirements for a Bomb

Plutonium in U.S. nuclear weapons is weapon-grade (about 6% Pu-240) in the form of delta-phase metal (density = 15.6 g/cc). The bare critical mass of delta-phase plutonium metal is dependent on the concentrations of the various plutonium isotopes, and varies from about 15 kg for plutonium with 6% Pu-240, to about 22 kg for plutonium with 30% Pu-240, reactor-grade plutonium from high burnup fuel. Thus, regardless of the fuel burnup level, the critical mass of plutonium will be between that of Pu-239 and U-235.[70]

The Trinity device (and the Nagasaki bomb) used 6.1 kg of weapon-grade plutonium, and modern compact fission warheads (using only plutonium) could require as little as 3 - 4 kg of weapon-grade plutonium. Consequently, a fission device could be made from as little as 6 to 10 kg of delta-phase plutonium recovered from high burnup fuel. As we proceed we will assume one bomb's worth of reactor-grade plutonium is about 8 kg (although in reality it can be smaller).

Plutonium with a high Pu-240 content is less desirable for weapons purposes than weapon-grade plutonium, because for low-technology weapons designs the neutrons generated by the high rate of spontaneous fission of Pu-240 can increase the statistical uncertainty of the yield by "pre-initiating" the chain reaction before the desired compression of the plutonium core has been achieved. Militarily useful weapons, with reliable yields in the kiloton range can be constructed based

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[70] J. Carson Mark, *Reactor-Grade Plutonium's Explosive Properties*, Nuclear Control Institute, August 1990. The bare critical masses of the fissile isotopes Pu-239 and Pu-241 are both about 15 kg. For the more brittle alpha-phase Pu-239, the bare critical mass is about 10 kg. The other isotopes of plutonium, Pu-238, Pu-240, and Pu-242, are fissionable by fast neutrons and as delta-phase metal have critical masses of about 15, 40 and 177 kg, respectively.

on low technology designs with reactor-grade plutonium. Using sophisticated designs, well within the capabilities of the U.S. and the Russian weapons programs, reliable light weight efficient weapons and high yield weapons whose yields have small statistical uncertainties can be constructed with plutonium regardless of the Pu-240 content.[71]

Pure PuO_2 as well as MOX blends with PuO_2 concentrations greater than about 20-30 percent appear to be directly usable in an illicit nuclear device.[72] However, the material requirements are substantially larger and the explosive yields of such devices would be substantially less than if plutonium metal were used, other design factors being the same.[73]

4.2b Plutonium Inventories in Breeder Fuel Cycles

As is becoming clear in both Russia, Japan and France, once reprocessing is sanctioned, the world is confronted with large flows of recovered plutonium and plutonium stockpiles. With a plutonium breeder economy the quantity of plutonium involved is staggering. The 280 Mw_e Monju in Japan requires 1.4 MT of fissile plutonium (Pu_f) for its initial core and 0.5 MT Pu_f annually thereafter. The 350 Mw_e CRBR in the U.S. was to have been loaded with 1.7 MT of plutonium (86% Pu-239), about the same Pu_f inventory as Monju.[74] The average annual fuel cycle requirements for CRBR are shown in Figure 2.

The plutonium inventory in a commercial-size breeder is about 5 MT, of which 3.5 MT is fissile[75] - about 600 atomic bombs worth. A Russian BN-800 would require

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[71] For further discussion see, J. Carson Mark, *Reactor-Grade Plutonium's Explosive Properties*, Nuclear Control Institute, August 1990; Thomas B. Cochran, et al., *Nuclear Weapons Databook, Volume I, U.S. Forces and Capabilities*, (Boston: Ballinger Publishing Company, 1984), p. 24, footnote 17.

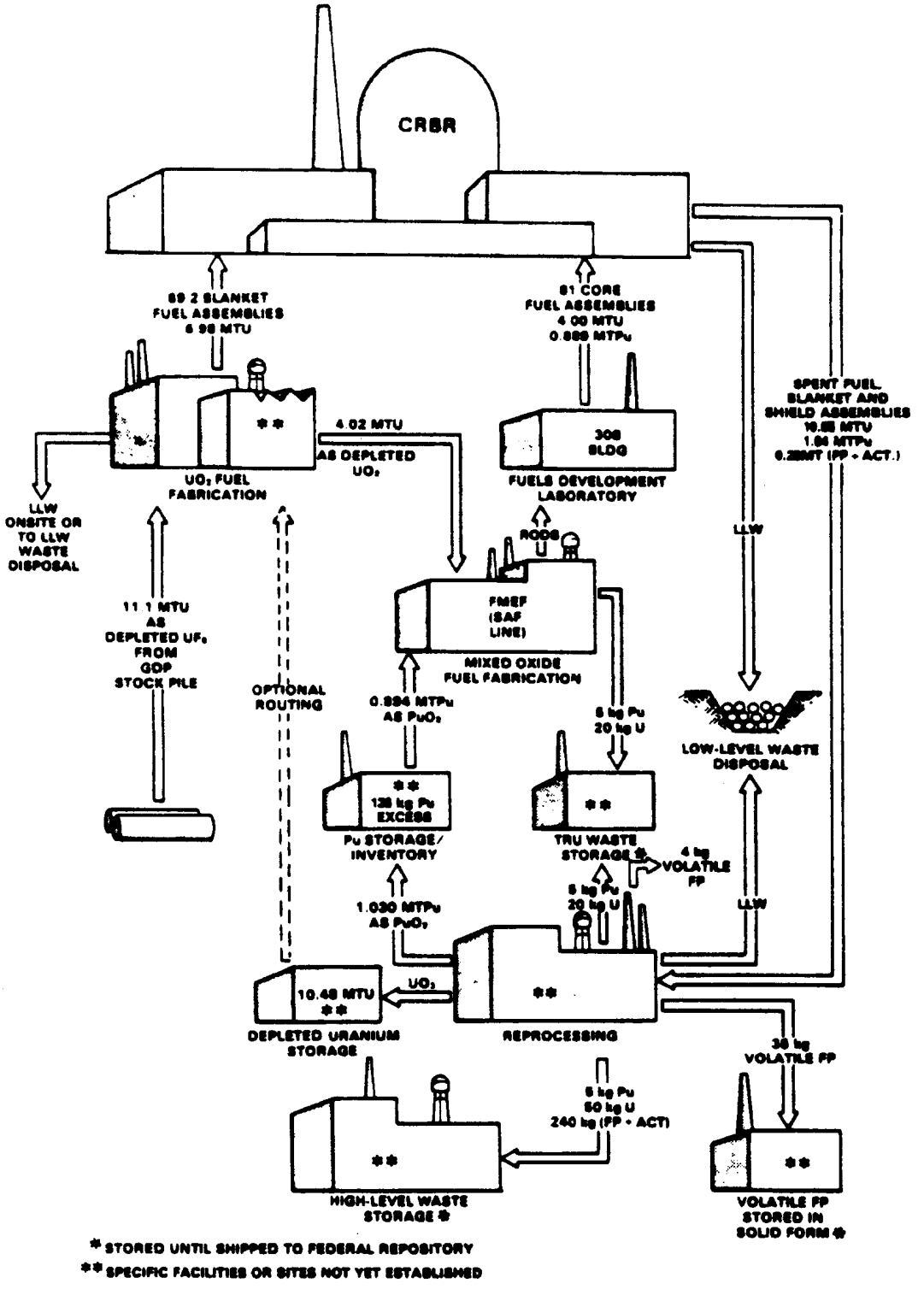
[72] U.S. Nuclear Regulatory Commission, *Safeguarding a Domestic Mixed Oxide Industry Against a Hypothetical Subnational Threat*, NUREG-0414, May 1978, p. 6-9.

[73] The bare critical mass for reactor-grade plutonium oxide (PuO_2) varies from 30 to 70 kg. Bare critical masses for MOX at 30 and 10 percent PuO_2 concentrations vary between 250 and 600 kg and 3,000 to 10,000 kg, respectively; ibid.

[74] U.S. Nuclear Regulatory Commission, *Safety Evaluation Report related to the construction of the Clinch River Breeder Reactor*, NUREG-0968, Vol. 1, Main Report, March 1983, p.4-122.

[75] The initial core of the Superphenix contained 5.2 MT of plutonium; Nuclear Engineering International, *World Nuclear Industry Handbook*, 1991, p. 126. European commercial FBR designs contain 3.4-4.1 MT of fissile plutonium; *Nucleonics Week*, April 28, 1988, p. 6.

Figure 2: Average Annual Requirements for CRBRP fuel cycle[76]



[76] Source: U.S. Nuclear Regulatory Commission, Supplement to Final Environmental Statement Related to Construction and Operation of Clinch River Breeder Reactor Plant, NUREG-0139, Supplement No. 1, Vol. 1, p. 5-17.

over 4 MT. Although the net amount of plutonium produced in a fast breeder reactor annually is generally less than that produced in a conventional thermal power reactor of the same size,[77] one-third to one-half of the FBR fuel must be removed annually for reprocessing, plutonium recovery, and remanufacture into fresh fuel.[78] Since the fuel will be outside of the reactor for 3.5 to 7 years the plutonium inventory needed to support a single commercial-size plutonium breeder is 11-22 MT, about 1300 to 2800 bombs worth. The RT-1 chemical separation plant at Chelyabinsk-65 has a capacity of 400-600 MTHM/y, although its throughput has averaged some 200 MTHM/y over the last 10 years. Processing low enriched uranium VVER spent fuel, it has the capacity to recover 3200-4800 kg plutonium annually, sufficient to construct 400-600 nuclear weapons. Up to 6000 weapons could be constructed from the plutonium recovered if it were processing breeder reactor fuel!

If only 10 Gw_e of nuclear capacity were supplied by breeders - hardly enough to justify the R&D effort in any country even if the economics were otherwise favorable - the plutonium inventory in the reactors and their supporting fuel cycle would be on the order of 100-200 MT, or about 12,000-25,000 bombs' worth. By comparison, U.S. nuclear weapons stockpiles in 1987 consisted of 23,400 warheads, and the weapon-grade plutonium inventory, most of which was in weapons, was about 100 MT. The Russian stockpile consists of about 130 MT of plutonium in about 30,000 warheads.

About one half of the plutonium created in a breeder reactor is bred in the blanket rods. The burnup of the blanket material is low. Consequently, the resulting plutonium is weapon-grade, with a Pu-240 concentration lower than that used in U.S. and Russian weapons. Thus, any non-weapons country that as large stocks of breeder fuel, has the capacity to produce a ready stock of weapon-grade plutonium. It only has to segregate and reprocess the blanket assemblies separately from the core assemblies.

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[77] The net excess fissile plutonium for a European design commercial FBR with a breeding ratio of 1.17 is 10 kg, while the excess is 194-220 for a design with a breeding ratio of 1.26; *Nucleonics Week*, April 28,1988, p. 6.

[78] Superphenix requires 1.1 MT of plutonium fuel annually; 0.9 MT of plutonium for the Japanese advanced reactor program; Frans Berkhout and William Walker, *Thorp and the Economics of Reprocessing*, Science Policy Research Unit, University of Sussex, November 1990.

4.2c Inadequate Security of Plutonium

Adequate physical security is essential to prevent the theft of any quantity of material, even as little as one bomb's worth. Highly accurate material accounting and control measures are essential to determine whether a theft has taken place and to provide timely warning to prevent the material from being used for illicit purposes. It is well established, from experience at existing civil and military chemical separation (reprocessing) plants, naval fuel facilities, and mixed-oxide fuel facilities, that it is impossible to provide a sufficient level of physical security, or material accounting and control, at bulk handling facilities that process large amounts of nuclear weapons-usable material.

1. Inadequate Physical Security. The difficulty in providing adequate physical security is that theft of materials can involve a collusion of individuals, including the head of the guard force, or even the head of the company. This was alleged to have occurred at the NUMEC facility in Apollo, Pennsylvania in the 1960s. Despite having guards at every bank, employees at the Bank of Credit and Commerce, Inc. (BCCI) allegedly were able to steal millions of dollars from bank customers because the thieves were running the bank - the collusion was at the top. If the threat includes the potential for collusion involving the guard force and company directors, providing adequate physical security in the West would require turning the facility into a heavily armed site occupied by an independent military force. In Russia physical security has relied on heavily guarding not only the facilities, but the towns where the work force resides. These closed cities are an anathema to a democratic society.

And of course the principal role of physical security is completely reversed when the collusion involves elements of the government itself. In this case the primary mission of the security apparatus is to hide the program from outside scrutiny. It is now known that at various times in the past, the governments of the United States, Japan (during World War II), Soviet Union, United Kingdom, France, China, Israel, India, South Africa, Sweden, Argentina, Brazil, Taiwan, Pakistan, North Korea, and Iraq have had secret nuclear weapons development programs.

2. Inadequate material accounting and control. Material accounting and control procedures, collectively referred to as safeguards, are meant to provide

timely detection of the diversion of significant quantities of weapons-usable material. The safeguards goals of the International Atomic Energy Agency (IAEA) have been summarized by Marvin Miller.[79] The IAEA's Standing Advisory Group on Safeguards Implementation (SAGSI) in 1977 defined a significant quantity of plutonium as 8 kg. The use of alpha phase plutonium, thicker reflectors, and compression by chemical explosives mean that the true significant quantity is considerably less -- on the order of 3 - 4 kilograms. This roughly corresponds to the critical mass of delta phase plutonium metal with a moderate neutron reflector.

To provide assurance that a significant quantity of fissile material has not been diverted, the uncertainty in the inventory accounting must be small compared to the quantity of fissile material considered significant, e.g., compared to 8 kg of plutonium or less. At a bank one can count every last yen, and this is done daily, and the books can be balanced precisely. At a bulk handling facility the books never balance because of material measurement errors. In the parlance of nuclear material accounting the inventory difference (ID) is defined as

$$ID = BI + I - R - EI,$$

where BI is the beginning inventory, EI is the ending inventory, and I and R are, respectively, the material added and removed during the inventory period.[80] For the minimum amount of diverted plutonium (assumed here to be 8 kg) to be distinguished from measurement noise with detection and false alarm probabilities of 95% and 5%, respectively, it can be shown that $3.3\sigma_{ID}$ must be less than 8 kg, where σ_{ID} is the uncertainty in the inventory difference.[81]

At existing reprocessing plants in the West that handle tons of weapons-usable plutonium, σ_{ID} is dominated by the error in measuring the plutonium input into the plant, which is about one percent of the throughput. The Japanese Tokai Mura plant, one of the smallest plants in the West, has a capacity of about 90 Metric Tons of Heavy Metal per year (MTHM/y), and the LWR spent fuel processed has an average total plutonium content of about 0.9 percent. Thus, $3.3\sigma_{ID}$ for Tokai

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[79] Marvin Miller, "Are IAEA Safeguards at Bulk-Handling Facilities Effective?," Nuclear Control Institute, Washington, D.C., August 1990.

[80] In the literature "inventory difference" (ID) is sometimes called "material unaccounted for" (MUF).

[81] Marvin Miller, op. cit.

Mura is about 27 kg of plutonium per annual inventory. Even if inventories were taken every six months, $3.3\sigma_{ID}$ would be about 14 kg, which is still greater than 8 kg. One simply cannot detect the diversion of several bombs' worth of plutonium annually from Tokai Mura.

We are told that there is essentially no material accounting and control at Russian plants handling nuclear fuel in bulk form. The RT-1 chemical separation plant at Chelyabinsk-65 has a capacity of 400-600 MTHM/y, and it has been operating at about 200 MTHM/y. Therefore, the situation at RT-1 would be two to six times worse than at Tokai Mura, even if it were brought up to current western standards. It is difficult to imagine running a bank where you never counted the money, or only counted the money twice a year, and then only counted the notes larger than 10,000 rubles. Yet the Russian nuclear establishment sanctions the commercial use of nuclear weapons-usable material under safeguards that are no better.

Detection time (the maximum time that should elapse between diversion and its detection) should be the same order of magnitude as the conversion time, defined as the time required to convert different forms of nuclear material into components of nuclear weapons. For metallic plutonium and HEU, conversion time was estimated by SAGSI as 7-10 days; for pure unirradiated compounds of these materials, such as oxides and nitrates, or for mixtures, 1-3 weeks.[82] These times are already much shorter than the period between cleanout inventories at any fuel reprocessing plant operating today. Thus, there can be no assurance that the primary objective of safeguards - the timely detection of significant quantities of plutonium - can be met.

To meet the timely detection criteria reprocessing plants would have to undergo clean-out inventories every few days, or weeks. But this would reduce their annual throughput - and utility - practically to zero. It would also drive up the cost of reprocessing. Plutonium recycle, the use of MOX fuel in LWRs, is already uneconomical due to the high cost of reprocessing. Similarly, the cost of the fast breeder fuel cycle is greater than that of the LWR operating on the once-through cycle, that is, without plutonium recycle.

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[82] Marvin Miller, op. cit.

In the West consideration is being given to Near-Real-Time Accountancy (NRTA) as a means of improving the sensitivity and timeliness of detection.[83] NRTA involves taking inventories at frequent intervals, typically once a week, without shutting down the facility. It and similar concepts are likely to be opposed by operators due to the added costs that would be imposed. In any case the method and adequacy of practical NRTA system implementation are open questions.[84]

3. International Implications. Controlling nuclear weapons proliferation will simply become impossible if the nuclear establishments in Russia and abroad continue with nuclear fuel reprocessing for plutonium recycle and wide-scale deployment of plutonium breeder reactors. As a consequence the shortest route to the acquisition of nuclear weapons would be through the civilian nuclear power program, as occurred in India, rather than through the construction of facilities dedicated to weapons production, as occurred in Israel. In this regard it is the unanimous opinion of the weapons design and arms control communities that it is not the capability to design a nuclear device which is the pacing consideration in a country's acquisition of a first weapon, but, instead, it is the availability of nuclear weapons materials which can be turned to weapons purposes.[85]

The reprocessing of spent fuel and the recycling of plutonium[86] in fresh fuel for reactors would allow non-nuclear weapons states to acquire and stockpile nuclear weapons-useable material - seemingly for peaceful purposes. Without violating any of the international safeguards agreements, countries could design and fabricate weapon components. By moving to a point of being within hours of having nuclear weapons - perhaps needing only to introduce the fissile material into the weapons - the nascent weapons state would have all of its options open.

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[83] Ibid.

[84] For a more detailed treatment of the deficiencies of international safeguards, see William Walker and Frans Berkhout, "International Safeguards and the New British and French Reprocessing Plants," Science Policy Research Unit, University of Sussex, DRAFT, 1991.

[85] Thomas B. Cochran, Russell E. Train, Frank von Hippel, and Robert H. Williams, *Proliferation Resistant Nuclear Power Technologies: Preferred Alternatives to the Plutonium Breeder*, ERDA, April 6, 1977, p. II-2.

[86] Or any other weapons material, such as highly enriched uranium or uranium-233.

Under these conditions, international safeguards agreements serve as a cover by concealing the signs of critical change until it is too late for diplomacy to reverse a decision to "go nuclear."

Acceptance of the plutonium breeder as an energy option provides the justification for the early development of a reprocessing capability by any country. A non-nuclear weapons country would always have the option to shift its "peaceful" nuclear program to a weapons program. Without national reprocessing facilities and breeder reactors, countries wishing to develop nuclear weapons capacity face very considerable political problems and cost. Obtaining large quantities of weapon-usable plutonium requires that they build one or more specialized production reactors. By establishing their nuclear weapons option through their nuclear electric generation program, they can circumvent these obstacles.

If Russia continues to develop its fast breeder program, other countries that want to preserve the weapons option will point to Russia as the basis for legitimizing their own breeder development efforts. India, as noted previously, recovered the plutonium for its first nuclear device in a reprocessing plant that was ostensibly developed as part of its national breeder program.

With the possible exception of the initial fuel inventory, the PRISM fuel will always contain radioactive fission products and actinides. Consequently, illicit diversion from the plant will be more difficult than diversion from the breeder fuel cycle currently employed. The PRISM design places plutonium metal fuel processing and manufacturing facilities at each reactor site. Also at the site will be a ready supply of about 25 MT of plutonium -- about 3000 bombs worth[87]. Finally, a large cadre of nuclear fuel specialists with hands-on experience in plutonium metallurgy will have access to these materials and equipment. No country that wants to preserve a nuclear weapons option could ask for a better cover for its military interest.

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[87] Assumes one reactor core and two reloads for each of nine 155 mw_e modules. A fresh fuel load for one module will contain about 1722 kg of plutonium (23% Pu-240). At each refueling (every 18 months), approximately 536 kg of plutonium will be discharged from, and 508 kg of plutonium loaded into, the reactor. Data supplied to the author by P.M. Magee, General Electric Company, September 13, 1991.

5. Energy Independence and the Breeder

The main selling points of the breeder are the promises that its fuel can be completely under national control, and that the fuel supply would be essentially inexhaustible. These illusory goals, however, are unachievable, or at best extremely costly, since there is no indication that breeder capital cost can be brought down to the level of LWR capital cost.

It is useful to ask whether there is another way of achieving a secure nuclear fuel supply without relying on nuclear weapons-usable material. We conservatively assume that a 1000 Mw_e LWR can be built today in the West for about $2000/kw,[88] and that the cost of an LMFBR would be only about 50% greater. We also ignore the fact that the cost of reprocessing and other breeder fuel cycle requirements is currently more than twice the cost of direct disposal of LWR fuel. (It is likely to remain at least twice the cost after the year 2000 assuming current uranium prices.[89]) Today the average price of imported U_3O_8 is about $30/kg.[90] By purchasing an LWR instead of a breeder, the $1,000 million capital cost saving could be used to buy 30,000 MT of U_3O_8 at today's prices, enough uranium to operate the LWR for about 150 years! If more advanced high burnup LWR fuels were used, the LWR could be operated for 300 years. While the economic situation in Russia is quite different, the ratio of the cost of a BN-800 to the cost

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[88] Charles Komanoff, *Variations in Nuclear and Coal Plant Capital Costs*, Komanoff Energy Associates, November 13, 1989. According to Komanoff for a sample of 30 U.S. nuclear plants completed during the period 1983-1991, the average cost of construction without interest was $2300/kw. One utility, Duke Power Co., was able to construct two plants for $1300/kw (1987 dollars). In 1991 dollars the costs would be about $2800/kw (30 plant avg.) and $1600/kw (Duke Power Co.) Adding 15% for real interest during construction would bring the costs to $3300/kw (avg.) and $1800/kw (Duke Power Co.)

[89] According to Frans Berkhout and William Walker, *Are Current Back-End Policies Sustainable*, Science Policy Research Policy Unit, University of Sussex, April 1991: The total undiscounted cost for the direct disposal of LWR fuel is around $900/kg of heavy metal (kgHM). Fuel reprocessing services at La Hague and Sellafield during the 1990s will cost between $1400-$1800/kgHM, not counting the cost of long term high level waste (HLW) storage, transportation and disposal. Even with the reduced prices now being offered for reprocessing in the post-2000 period - $900/kgHM - reprocessing seems to double the cost of dealing with spent fuel, assuming that vitrified HLW cost about as much to bury as spent fuel. Even if the plutonium is treated a free good, MOX fuel is more costly than low enriched uranium fuel given the higher cost of fabrication of MOX fuel.

[90] The average price of uranium imported into the United Stated in 1990 was 12.56 per pound, a decrease of 25 percent from the 1989 price; U.S. Department of Energy, Energy Information Administration, *EIA Reports*, EIA-91-12, June 24, 1991.

of a VVER is also at least 1.5, Therefore the results will be similar. Moreover, given the enormous surplus of enriched uranium from weapons to be retired, the economics of the breeder should be worse, not better in Russia.

Clearly, if energy independence, or wise economic investment were the objective, countries like Russia would abandon their breeder programs and invest in technologies that could improve the overall economies.

6. Actinide Burning.

The concept of burning actinides in fast reactors is an old one that has received renewed interest in the West in light of difficulties in developing national high-level radioactive waste repositories. With actinide burning, many of the longest-lived radioactive isotopes that would otherwise end up in the high level waste are transmuted into shorter-lived isotopes in the reactor. The fission cross section of a fast reactor offers the prospect of transmuting actinides more efficiently than thermal reactors do. In the IFR fuel cycle (selected as the reference fuel cycle for the PRISM reactor) the plutonium metal fuel is pyroprocessed on site. Pyroprocessing offers a relatively uncomplicated means of actinide recovery, so that the actinides can be recycled back into the reactor along with the plutonium. The IFR fuel cycle is advertized as providing "a means to substantially reduce the toxicity risk associated with these wastes streams from tens of thousands of years to hundreds of years" (Figure 3).[91] But, as demonstrated by Thomas Pigford, Professor of Nuclear Engineering at the University of California, Berkeley, this is not the case.[92]

As Pigford concluded, "calculated 'toxicities,' used to support the goals stated by the ALMR program, are not measures of risk. Use of 'toxicity' and the assumption that it is a measure of risk have led to incorrect conclusions of safety benefits from actinide burning."[93]

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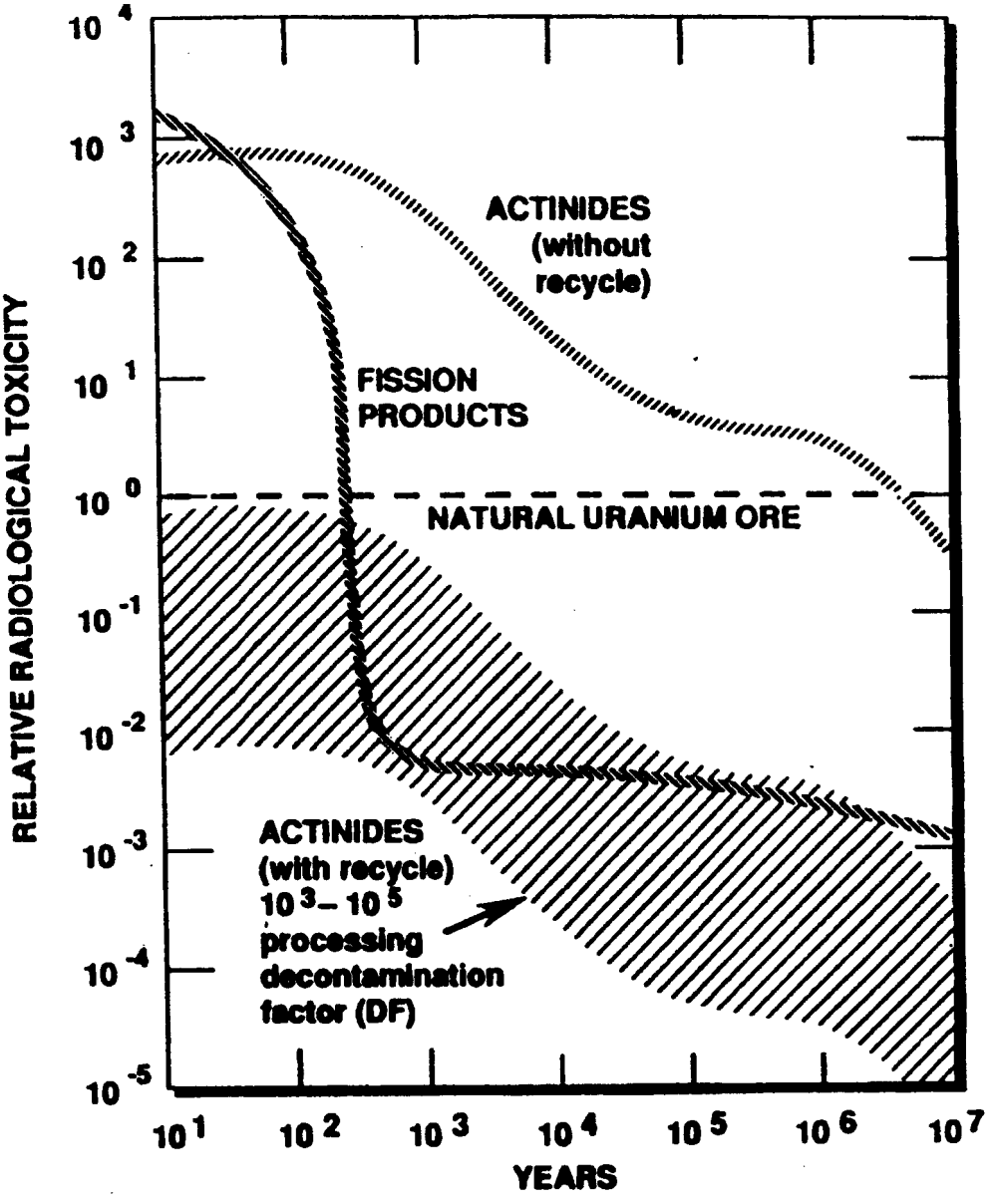
[91] C.E. Boardman and C.R. Snyder, "Advanced Liquid Metal Reactor (ALMR) Desalinization/Electric Plant," Paper presented at the Sixth International Conference on Emerging Nuclear Energy Systems, Monterey, CA, June 16-21, 1991.

[92] Thomas H. Pigford, "Actinide Burning and Waste Disposal," *Proceedings of the First international Conference on the Next Generation of Nuclear Power Technology*, Massachusetts Institute of Technology, October 4-5, 1990, MIT-ANP-CP-001, pp. 8-19 to 8-53.

[93] Ibid, pp. 8-20 to 8-22.

Figure 3: Timed Phased Relative Waste Toxicity (LWR Spent Fuel)



"A direct measure of risk from radionuclides in repository waste is the maximum radiation dose to future human beings who may be exposed to radionuclides that finally reach the environment. These doses are being calculated by repository projects in the U.S. and in other countries as a key part of the environmental and safety analyses for geologic disposal. A U.S. regulation requires that radiation doses from radioactive waste buried in a geologic repository be calculated for times far into the future, much longer than 10,000 years. Because of their low solubilities and their sorption in the geologic media, actinides from spent fuel waste contribute far less radiation dose than do the fission products.[94] "...The long-lived fission products will be in the waste even if actinides are removed and even if the separated wastes are stored on the surface for 200-300 years."[95] Pigford also noted that "[c]ontrolling waste streams will be crucial to reprocessing for the ALMR, particularly the many secondary waste streams of low concentration and high volume. Reprocessing generates large amounts of alpha-contaminated dilute waste streams that are very difficult to decontaminate further or to immobilize in a safe waste matrix for geologic disposal. If further decontamination, to the very low levels necessary to qualify as low level waste, is not practicable, these wastes would have to be disposed of in deep geologic repositories. They would have to be concentrated, or they would occupy far larger waste volumes than spent fuel or other high-level waste. The potential problem of primary and secondary wastes from reprocessing has not been sufficiently addressed by the ALMR program. The cost of disposing of the expected large volumes of decontaminated low-level waste has not been addressed."[96]

"Recovering actinides from LWR fuel and recycling them in an ALMR breeder reactor builds up large inventories of actinides in the breeder reactor and fuel cycle. It will take thousands of years of operation before the actual total inventory of actinides in waste and in the above-ground fuel cycle is significantly lower than

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[94] Ibid.

[95] Ibid.

[96] Ibid.

the total inventory of actinides in repositories without actinide burning. The relative risks have not been analyzed."[97]

In sum, as Pigford notes, "[t]here are several technical incentives to reprocessing spent fuel rather than burying it directly in a geologic repository, including:

* a waste form that is less reactive in the oxidizing environment of unsaturated rock, and
* simple concentrated waste forms of the more soluble long-lived radionuclides carbon-14, technetium-99, iodine-129, and cesium-135.

These incentives could be realized by reprocessing the LWR fuel, without high-yield recovery of all the actinides. However, using realistic cost data, the cost of reprocessing for this purpose is prohibitive. It hasn't been proven that changing the waste form by reprocessing is necessary for the successful performance of a high-level waste repository."[98]

7. Conclusion

The countries with advanced nuclear programs have spent tens of billions of dollars over a forty-five year period trying to commercialize the fast breeder reactor. Today they are no closer to that goal than when they started. Even the most ardent breeder enthusiasts continue to predict commercialization three to four decades away, just as they were predicting two decades ago. There is now overwhelming evidence based on the construction of demonstration and commercial-size fast breeder reactors in France, Germany, Russia, and Japan that the breeder has no hope of competing with alternative energy supply technologies, including LWRs operating on the once-through fuel cycle. The fast breeder is a terrible economic investment.

From a reactor reliability standpoint the technology has been unforgiving. The U.S. EBR-I and Fermi-I reactors both experienced fuel melting, and the latter was permanently shut down; the Soviet BN-350 experienced a serious sodium fire, and

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[97] Ibid.

[98] Ibid.

the BN-600 has had fuel and steam generator problems; the French Phenix and Superphenix reactors have been plagued with sodium related problems and are now shut down, perhaps permanently; and the Indian PFBR has had a similarly poor operating history. The German Kalkar could not obtain an operating license for safety reasons.

One of the arguments for breeders has been that they will provide energy security. The economic prospects for the breeder, however, are now so poor that it is far cheaper, and quicker, to provide fuel security by stockpiling uranium, rather than by building breeders and their associated fuel cycle facilities.

Fast reactors also are being touted as simplifying the high level nuclear waste disposal problem by recovering the actinides in spent fuel and burning them. But on close examination this does not represent a significant improvement in waste management, and may actually make matters worse.

From a reactor safety standpoint the plutonium fast breeder has to be considered one of the more dangerous reactor technologies. At the very least, the risks are not well understood. In certain scenarios the reactor can literally blow its top. The probability that these "paper" scenarios may actually materialize is not known.

The development of a breeder economy will require the flow of tens to hundreds of tons of nuclear weapons-usable plutonium annually in the fuel cycle. Providing adequate physical security to prevent the diversion of a few kilograms of plutonium for illicit weapons purposes is impossible. There is no credible material accounting and control regime that can be applied to commercial-size bulk handling facilities to provide the necessary assurance that a diversion can be detected in a timely fashion.

If Russia continues with its program of nuclear fuel reprocessing and breeder development it will be establishing an international norm of behavior that will make it impossible to control the spread of nuclear weapons or reduce the large stockpiles of nuclear weapons that currently exist.

With vast quantities of nuclear weapons material flowing through its fuel cycle, the greatest risk of the plutonium breeder is that of nuclear proliferation.