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India and Fast Breeder Reactors

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India has long pursued a fast breeder program, motivated in part by the availability of only poor quality uranium resources within the country. But progress so far has been disappointing, with only one test reactor having been constructed and having a chequered operating history. The larger Prototype Fast Breeder Reactor that is being constructed has a design that compromises safety and will produce expensive electricity, but could be used as a way to convert reactor-grade plutonium to weapon-grade plutonium. Projections offered by the nuclear establishment of fast growth of breeder reactors are methodologically flawed and based on very optimistic assumptions.

INTRODUCTION

India is one of only two countries currently constructing commercial scale breeder reactors (the other is Russia). Both the history of the program and the economic and safety features of the reactor suggest, however, that the program will not fulfill the promises with which it was begun and is being pursued.

HISTORY

Breeder reactors in India were originally proposed in the 1950s as part of a three-stage nuclear program as a way to develop a large autonomous nuclear power program despite India's relatively small known resource of uranium ore.[1]

The first stage of the three-phase strategy involves the use of uranium fuel in heavy water-reactors, followed by reprocessing the irradiated spent fuel to extract the plutonium.

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In the second stage, the plutonium is used to provide startup cores of fast breeder reactors. These cores would be surrounded by "blankets" of either depleted or natural uranium, to produce more plutonium. If the blanket were thorium, it would produce chain-reacting uranium-233. To ensure that there is adequate plutonium to construct follow-on breeder reactors, however, breeder reactors would have to be equipped with uranium blankets until the desired nuclear capacity was achieved.

The third stage would involve breeder reactors using uranium-233 in their cores and thorium in their blankets.

The three-stage program remains the official justification for pursuing breeders, despite their slow and disappointing progress.

Though India's Department of Atinuc Energy (DAE) has been talking about breeder reactors since its inception, work on even conceptual studies on breeders began only in the early 1960s. In 1965, a fast reactor section was formed at the Bhabba Atomic Reseach Center (BARC) under S. R. Paranjpe and design work on a 10-MWe experimental fast reactor was initiated.[2] This seems to have been abandoned and, in 1969, the DAE entered a collaboration agreement with the French Atomic Energy Commission (CEA) and obtained the design of the RAPSODIE test reactor and the steam generator design of the Phenix reactor.[3] This was to be the Fast Breeder Test Reactor (FBTR), India's first breeder reactor.

As part of the agreement with the CEA, a team of about thirty Indian engineers and scientists were trained at Cadarache, France. Once they returned, they formed the nucleus of the Reactor Research Centre (RRC) that was set up in 1971 at Kalpakkam to lead the breeder effort. In 1985, this was renamed the Indira Gandhi Centre for Atomic Research (IGCAR). Over the years, the center has emerged as the main hub of activities related to India's breeder program.

THE FBTR EXPERIENCE

The budget for the Fast Breeder Test Reactor was approved by DAE as early as September 1971 and it was anticipated that the FBTR would be commissioned by 1976.[4] But the reactor finally attained criticality only in October 1985; and the steam generator began operating only in 1993.[5]

Much of the first one and a half decades of the FBTR's operations were marred by several accidents of varying intensity. Two of these are described below in some detail to illustrate the complexities of dealing with even relatively minor accidents and the associated delays, as well as the hazards posed to workers. When viewed in combination with similar experiences elsewhere, these suggest that it is unlikely that sodium-cooled breeder reactors will ever perform with the reliability that water-cooled burner reactors have demonstrated over the last couple of decades.

In May 1987 there was a major incident that took two years to rectify.[6] This occurred as a fuel subassembly was being transferred from the core to the periphery.[7] The problem began with the failure of a logic circuit involved in the rotation of the plug to move the selected fuel assemblies. For some reason, this logic circuit was bypassed and the plugs were rotated with a foot long section of one fuel subassembly protruding into the reactor core. This resulted in the bending of that specific subassembly as well as the heads of 28 reflector subassemblies on the path of its rotation. Various maneuvers to rectify the situation did not help and only resulted in one reflector subassembly at the periphery getting ejected as well as the bending of a "sturdy guide tube" by 32 cm. The last event has been described as the result of "a complex mechanical interaction" which seems to suggest that how it happened was never really understood.

Extensive repairs were required before the reactor could be restarted. First, the guide tube had to be cut into two parts using a "specially designed remote cutting machine" while ensuring that none of the chips produced during the cutting process fell into the core.[8] Then the damaged reflector subassemblies had to be identified using a periscope. Finally part of the sodium had to be drained out and the damaged subassemblies removed using specially designed grippers. Needless to say, all of this took time and reactor operations commenced only in May 1989.[9]

The second accident described here is one that is common in fast breeder reactors—a sodium leak. That this occurred 17 years after the reactor was commissioned underlines the generic nature of such accidents. The leak occurred in September 2002 inside the purification cabin, which houses the pipelines of the primary sodium purification circuit.[10] The cause of the leak is said to have been "the defective manufacturing process adopted in the manufacture of the bellows sealed sodium service valves." By the time the leak could be confirmed and controlled, about 75 kg of sodium had spilled over and solidified on the cabin floor and various components in that cabin.

Removing this radioactive sodium was a major effort. To begin with, even to approach the cabin, the workers had to wait ten days to allow for a reduction in the radioactive activity from the sodium, some of which had absorbed a neutron to become Na-24, a gamma emitter (15-hour half-life). Even then, in areas near the spilled sodium, the dose rate was as high as 900 milli-Sieverts per hour (mSv/h).[11] Another problem resulted from the whole cabin normally being surrounded by a layer of nitrogen so as to avoid burning of sodium. At first, IGCAR tried to simply replace the nitrogen with regular air so that cleanup workers could breathe. But this led to sparks and fires involving the spilled sodium. These had to be put out with dry chemical powders—but then this led to lots of dust being suspended in the atmosphere and made visibility poor. Once again nitrogen had to be reintroduced. Workers were then sent in with masks that had tubes feeding them with breathing air. Much of the work had to be done remotely, which, while lowering radiation exposure, made it a very slow operation. In all, removing the 75 kg of sodium and bringing the cabin back to normal conditions took about three months.[12]

The FBTR experience has also seen several other accidents and unusual occurrences, such as unexplained reactivity transients.[13] Overall, the reactor's performance has been mediocre: it took 15 years before the FBTR even managed 50 plus days of continuous operation at full power.[14] In the first 20 years of its life, the reactor has operated for only 36,000 hours, implying that the availability factor is only about 20 percent.[15] Despite this checkered history, IGCAR claims to have "successfully demonstrated the design, construction and operation" of a fast breeder reactor.[16]

THE PROTOTPE FAST BREEDER REACTOR

Even before the FBTR came on line, the DAE started making plans for a larger Prototype Fast Breeder Reactor (PFBR). In 1983, the DAE requested the government for budgetary support.[17] The first expenditures on the PFBR started in 1987–88.[18] In 1990, it was reported that the government had "recently approved the reactor's preliminary design and has awarded construction permits" and that the reactor would be on line by 2000.[19] Construction of the reactor finally began in October 2004 and was projected to be commissioned in 2010.[20] It will also be a source of weapon grade plutonium that might be used for the strategic program (see below).

Though it has not yet been constructed, the PFBR will likely suffer from the two problems that have plagued breeder reactors elsewhere: the risk of a catastrophic accident and poor economics.

Safety

There are a number of reasons to doubt the safety of the PFBR design.[21] As with other breeder reactors, the PFBR design is susceptible to catastrophic accidents involving large and explosive energy releases and dispersal of radioactivity following a core meltdown. The potential for such "Core Disruptive Accidents" (CDA) comes from the reactor core not being in its most reactive configuration. If conditions during an accident cause the fuel bundles to melt and rearrange, the reactivity could increase leading to further core rearrangement and a potential positive feedback loop. Another unsafe feedback effect that is present in the PFBR design is its positive sodium void coefficient. This means that if the coolant heats up and becomes less dense, forms bubbles, or is expelled from the core, the reactivity increases. The magnitude of the void coefficient is a measure of the feedback and tends to increase with core size.[22]

Table 1: Containment design specifications of demonstration fast reactors.

Name	Thermal Power E (MWth)	Sodium void coefficient ($)	Volume V (m^3)	Pressure (kPa)	V*P/E (kNm/MWth)
Phenix	563	—	31000	40	2.20E+03
PFR	650	2.6	74000	5	5.69E+02
CRBRP	975	2.29	170000	170	2.96E+04
SNR-300	762	2.9	323000	24	1.02E+04
MONJU	714	—	130000	30	5.46E+03
PFBR	1250	4.3	87000	25	1.74E+03

Source: Calculations based on data from IAEA Fast Reactor Database (IAEA, "Fast Reactor Database: 2006 Update.")

For the core design that has been adopted for the PFBR, it has a value of 4.3 $ ("dollars").[23]

Compounding the safety risks that come with this large and positive sodium void coefficient, the PFBR design also has a relatively weak containment, which is designed to withstand only 25 kiloPascals (kPa) of overpressure.[24] This maximum overpressure that the PFBR containment is designed for is low compared to most other demonstration reactors (Table 1), If one considers the ratio of the containment volume times its design overpressure divided by the reactor power, V*P/E, the PFBR containment is weaker than those of all other reactors except the Prototype Fast Reactor (PFR).[25] The difference appears more acute when the higher positive sodium void coefficient of the PFBR in comparison to other breeder reactors is taken into account.

It is of course possible to design containments to withstand much higher pressures. Containments for light water reactors routinely have design pressures above 200 kPa.[26] The DAE justifies this choice of containment design by arguing that its safety studies demonstrate that the maximum overpressures expected in a Core Disruptive Accident (CDA) are smaller than this overpressure. But these are based on favourable assumptions, in particular, that only limited parts of the reactor core would participate in the CDA and that only about 1 percent of the thermal energy released would be converted into mechanical energy. Based on such assumptions, the DAE estimates that the maximum credible energy release in a CDA is 100 MegaJoules (MJ).[27] It then calculates that such a CDA leading to sodium leakage into the containment will result in a containment overpressure of 20 kPa.

There are, however, good reasons to consider much larger energy releases from a worst-case CDA to the extent of several hundreds of MegaJoules in the evaluation of the safety of a reactor design, especially one as large as the PFBR. Table 2 shows that the calculated CDA energy releases for a number of breeder reactors are much higher than that of the PFBR, both absolutely and when scaled by reactor power.

Table 2: Maximum CDA work energy calculations for FBR systems.

Reactor	Year critical	Power (MWth)	Approximate maximum CDA work energy (MJ)	CDA/power ratio
Fermi	1963	200	2000	10
EBR-II	1964	65	600	9.2
SEFOR	1969	20	100	5
PFR	1974	600	600–1000	1–1.7
FFTF	1980	400	150–350	0.4–0.9
SNR-300	1983 (anticipated)	760	150–370	0.2–0.5
PFBR	2010	1200	100	0.083

The energy releases from core collapse depend sensitively on the reactivity insertion rate, which is the rate at which the fuel rearrangement increases ("inserts") reactivity.[28] The DAE's calculation of the maximum CDA energy release is based on a reactivity insertion rate of 65 $ per second, which itself is the result of assuming only limited amounts of core involvement in disassembly.[29]

The choice of reactivity insertion rate is questionable. There is ample reason and precedent to use an insertion rate of 100 $/s as a benchmark for disassembly calculations, with the caveat that it still is not quite an upper bound.[30] Likewise, the efficiency of conversion could be much larger than the 1 percent assumed by the DAE. Tests at the UK's Winfrith facility with core melt amounts of up to 25 kg suggest energy-conversion efficiencies of about 4 percent.[31] For a reactivity insertion rate of 100 $/s, and an energy conversion efficiency of 1 percent, the energy release from a CDA is 650 MJ.[32] It has been estimated that a 650 MJ CDA could lead to an overpressure of about 40 kPa on the containment, clearly much higher than the design limit of the containment building.[33] Higher conversion factors would imply higher mechanical energy releases and thus higher overpressures and higher likelihoods of containment failure.

To summarize, there are good reasons to believe that the containment of the PFBR does not offer adequate protection against a severe CDA, especially given the many uncertainties inherent in calculations of CDA release energies.

ECONOMICS

The main argument offered for the DAE's pursuit of breeder reactors is that that India has only "modest uranium reserves" of about 60,000 tons, "which can support 10 000 MWe (megawatt electric) of PHWR [pressurized heavy-water reactor] capacities."[34] While widely repeated, this formulation is misleading. India's uranium resource base cannot be represented by a single number. As with any other mineral, at higher prices it becomes economic to mine lower grade and less accessible ores. Exploiting these would increase the amount of uranium available. Therefore, uranium resources can only be specified as a function of price.

As a way of evaluating the economics of breeder reactors, the cost of generating electricity at the 500 MWe PFBR with a 700 MWe PHWRs,[35] the mainstay technology of the Indian nuclear program, have been compared.[36] In order to address the argument about India's limited uranium reserves, this has been done as a function of uranium price and the crossover price when the two technologies generate electricity at the same cost has been calculated.

The total construction cost of the PFBR is estimated as Rs. 34.92 billions (mixed year Rupees; overnight construction cost of $646 millions in 2004 dollars). The overnight unit cost is $1292/kW and is lower than the corresponding figure for recent Indian PHWRs of $1371/kW. This is quite in contrast with experiences around the world that suggest that breeder reactors are much more expensive than water moderated reactors; for Light Water Reactors (LWRs), a typical estimate of the cost difference is $200/kW.[37] The PFBR's estimated construction cost is also much lower than estimates of breeder reactor construction costs elsewhere; the Nuclear Energy Agency (NEA) gives a range of $1850–2600/kWe (2000 dollars) or $2000–2800 (2004 dollars) for MOX fueled fast reactors.[38] Actually constructed breeder reactors in other parts of the world also bear out the expectation of higher costs. Construction costs for the French Phénix reactor with a capacity of 250 MWe totalled FRF_{1974}800 million ($800 million in 2004 Dollars) or $3200/kW. However, a further 600 million ($870 million in 2004 Dollars) were spent on Phénix upgrades between 1997 and 2003. The 1240 MWe Superphénix was even more expensive. For these technical reasons, and the DAE's history of cost overruns at *all* the reactors it has constructed, it is fairly likely that the PFBR capital cost will be higher than this projected value.

In economic terms, the primary material requirement for the PFBR is plutonium. The PFBR design requires an initial inventory of 1.9 tons of plutonium in its core.[39] Based on a detailed model of the reactor, it has been estimated that at a 75 percent capacity factor, the PFBR requires 1012 kg of plutonium every year for refueling during equilibrium conditions.[40] The plutonium for the initial core and the first few reloads will have to come from reprocessing of PHWR spent fuel. At a real discount rate of 6 percent, reprocessing costs about $659 per kg of uranium in the fuel, which corresponds to a plutonium cost of $178/g.[41] Because of the higher plutonium content of the PFBR spent fuel, the unit cost of subsequent plutonium requirements would be lower, about $43/g.[42]

Following the Nuclear Energy Agency, the costs of fabricating breeder-reactor core fuel and (radial) blanket uranium fuel have been assumed to be $1512/kg and $540/kg.[43] The base case assumes costs of $200/kg for natural uranium and $200/kgU for fabrication of uranium fuel for heavy-water reactors.

Table 3 shows the difference in the levelised cost, at a real discount rate of 6 percent, of producing electricity at the PFBR and at the proposed 2 $\times$ 700 MW PHWRs (twin unit).[44]

Table 3: Cost of electricity from breeder and heavy water reactors.

	PFBR (500 MWe)	PHWR (2 × 700 MWe)
Overnight construction cost (Million 2004 $)	646	1588
Real discount rate (%)	6	6
Capital cost (present value) (Million 2004 $)	504	987
Capacity factors (%)	80	80
Lifetime plutonium/uranium cost (Million 2004 $)	1480	697
Total lifecycle cost (Million 2004 $)	2212	2550
Levelised cost (Rs/kWh)	2.77	1.54
Levelised cost (cents/kWh)	6.30	3.49
Percentage difference (PFBR-PHWR)	80%	

Note: All figures in 2004 U.S. dollars unless noted otherwise.

The economics of the PFBR will be key to the future of breeder reactors in India. The DAE has argued that the "primary objective of the PFBR is to demonstrate techno-economic viability of fast breeder reactors on an industrial scale."[45] The results presented here show that the PFBR will not be viable, even at the projected costs and for optimistic assumptions about capacity factors.

As Table 4 shows, breeder reactors across the world have operated with relatively low cumulative load factors. There is no reason to expect that the PFBR experience would not be similar, and a capacity factor of 50 percent might well be more plausible. This would result in a levelised cost of 8.35 cents/kWh, 139 percent more expensive than PHWRs.

As mentioned earlier, the main rationale offered for the pursuit of expensive breeders is the shortage of uranium. The validity of this rationale has been examined by increasing the price of uranium from $200/kg to the "crossover value" where breeders become competitive. For the optimistic base case, with a PFBR capacity factor of 80 percent, the levelised costs of electricity from the PFBR and PHWR are equal at a uranium price of $1375/kg. At a PFBR capacity factor of 50 percent, the crossover price is $2235/kg.

Table 4: Reliability of breeder reactors.

	PFR	BN-600	Phenix	Superphenix
Date of construction start	1 January 1966	01 January 1969	01 November 1968	13 December 1976
Date of first Criticality	1 March 1974	26 February 1980	31 August 1973	07 September 1985
Date of grid connection	10 January 1975	08 April 1980	13 December 1973	14 January 1986
Cumulative load factor	23.87%	73.48%	41.34%	6.6%

These prices are much higher than current values and significantly larger quantities of uranium will be available at these prices. The distribution of uranium among the major geological reservoirs in the earth's crust corresponds to a roughly three hundred fold increase in the estimated amount of recoverable uranium for every ten fold decrease in the ore grade.[46] Based on this, and assuming that mining cost is inversely proportional to ore grade, one can surmise that the available uranium at costs less than $1375/kg and $2235/kg are about 124 and 417 times current reserves respectively. This is an underestimate because it ignores the general trends of reduced mining costs due to learning and improved technology.[47] In any case, India should have sufficient uranium for decades based on PHWRs, with no reprocessing and breeder reactors.

Plutonium for Weapons?

There may be another reason for the DAE's attraction to breeder reactors. This stems from the source of DAE's institutional clout: its unique ability to offer both electricity for development and nuclear weapons for security. This came out quite clearly during the course of negotiations over the U.S.-India nuclear deal, where in an ostensibly civilian agreement, much of the DAE's efforts were aimed at optimising its ability to make fissile material for the nuclear arsenal within various constraints, especially the shortage of uranium.[48] Most prominently, the DAE's focused a lot of attention on keeping the fast breeder program outside of safeguards. In a prominent interview with a national newspaper, the head of the DAE said: "Both, from the point of view of maintaining long-term energy security and for maintaining the minimum credible deterrent, the fast breeder programme just cannot be put on the civilian list. This would amount to getting shackled and India certainly cannot compromise one [security] for the other."[49]

In parallel, the DAE did not classify its reprocessing plants or its stockpile of reactor-grade plutonium as civilian. This allows for the possibility that breeder reactors like the PFBR are used as a way to "launder" unsafeguarded reactor-grade plutonium, both the historical stockpile as well as future production at unsafeguarded reprocessing plants, into weapon-grade plutonium. While reactor-grade plutonium is consumed in the core of the PFBR, in the radial and axial blankets weapon-grade plutonium is produced. Based on neutronics calculations for a detailed three-dimensional model of the reactor, it has been estimated that 92.4 kg and 52 kg of weapon-grade plutonium will be generated in the radial and axial blankets (93.7% and 96.5% Pu-239) respectively in the PFBR each year at 75 percent capacity factor.[50]

If the blanket fuel elements are reprocessed separately rather than jointly with the core fuel elements, then the plutonium contained in them can be used for weapons. To make up for this, about 346 kg of reactor-grade plutonium derived from reprocessing spent fuel from India's PHWRs would have to be used in the PFBR annually. The existing stockpile of reactor-grade plutonium and PHWR spent fuel is adequate to meet this need for decades. Such a strategy would increase the DAE's weapon-grade fissile material production capacity several-fold.

FUTURE PROJECTIONS

The PFBR is to be the first of the many breeder reactors that the DAE envisions building. The DAE's current projections are that nuclear power would grow to 20 GW by 2020 and to 275 GW by 2052, including 260 GW in metallic fueled breeders.[51] More recent media statements following the NSG waiver project even larger rates of growth of India's breeder capacity. These seem to assume that spent fuel from imported Light Water Reactors fueled with imported uranium will be reprocessed and the plutonium extracted will also be used to provide startup fuel for breeder reactors.

These projections are primarily based on assumptions about the doubling time, the time it would take a breeder reactor to produce enough plutonium to fuel a new breeder reactor core. Since MOX fuelled reactors have lower breeding ratios, by 2020 the DAE plans to switch to constructing breeders that use metallic fuel, which could have a much higher breeding ratio.[52] A higher breeder ratio will result in a shorter doubling time. The rate of growth also depends sensitively on the out-of-pile time, the time period taken for the spent fuel to be cooled, reprocessed, and fabricated into fresh fuel. The DAE assumes very optimistically that all of this can be accomplished within one year.[53]

The DAE's methodology is flawed, however, and does not account correctly for plutonium flows.[54] To start with, the base capacity of MFBRs assumed in 2022 of 6 GW, which is necessary for the 2052 projection, would require about 22 tons of fissile plutonium for startup fuel. The DAE does not have enough reprocessing capacity currently to handle all the spent fuel produced by the heavy water reactors that are operating and under construction. Even if the DAE does manage to inexplicably obtain the necessary plutonium to construct a MFBR capacity of 6 GW with some to spare, under the DAE's assumed rate of growth, the plutonium stockpile would *reduce* by about 40 tons just in the first ten years. This is because there is a lag of three years between the time a certain amount of plutonium is committed to a breeder reactor and it reappears in the form of more plutonium for refuelling the same reactor and to contribute to the startup fuel for a new breeder reactor, even with an optimistic one year out-of-pile time.

A more careful calculation taking into account the plutonium flow constraints shows that the capacity for MFBRs based on plutonium from the DAE's heavy water reactor fleet will come down from the projected 199 GW to 78 GW by 2052.[55] If the out-of-pile time were to be chosen to be a more realistic three years, the MFBR capacity in 2052 based on plutonium from PHWRs will drop to 34 GW.

While these figures may seem large compared to India's current nuclear capacity of only 4.1 GW, they should be viewed in relation to the projected requirements, under business-as-usual conditions, of about 1300 GW by mid-century. Further, the only constraint assumed here is fissile material availability. It assumes that there will be no delays because of infrastructural and manufacturing problems, economic disincentives due to the high cost of electricity, or accidents. All of these are real constraints and render even the lower end of the 2052 projections quite unrealistic.

CONCLUSION

Breeder reactors have always underpinned the Indian DAE's claims about generating large quantities of cheap electricity that was seen as necessary for development. Today, more than five decades after those plans were announced, that promise is yet to be fulfilled. As elsewhere, breeder reactors are likely to be unsafe and costly, and their contribution to overall electricity generation will be modest at best.

NOTES AND REFERENCES

1. H. J. Bhabha and N. B. Prasad, "A Study of the Contribution of Atomic Energy to a Power Programme in India" (paper presented at the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958).

2. S. B. Bhoje, "History and Evolution of Fast Breeder Reactor Design in India—a Saga of Challenges and Successes," IGC Newsletter, July 2006.

3. Placid Rodriguez, "Foresight, Vision, and Strategy in the Management of Fast Breeder Technology in India," *International Journal on Foresight and Innovation Policy* 1(3/4) (2004).

4. CAG, "Report by the Comptroller and Auditor General of India," (New Delhi: Comptroller and Auditor General of India, 1993).

5. Mark Hibbs, "Kalpakkam FBR to Double Core, Load First Thorium-232 Blanket," *Nucleonics Week* 38(48) (1997).

6. G. Srinivasan et al., "The Fast Breeder Test Reactor—Design and Operating Experiences," *Nuclear Engineering and Design* 236 (2006).

7. R. P. Kapoor et al., "Unusual Occurrences in the Fast Breeder Test Reactor," in Technical Committee Meeting on Unusual Occurrences During LMFBR Operation (Vienna, Austria: International Atomic Energy Agency, 1998).

8. Srinivasan et al., "The Fast Breeder Test Reactor—Design and Operating Experiences."

9. In July 1989, the reactor was shut down again due to noise pick-up by the reactor protection logic and unsatisfactory operation of the speed control system for the primary sodium pumps CAG, "Report by the Comptroller and Auditor General of India."

10. K. Sasikumar, V. S. Krishnamachari, and P. V. Ramalingam, "Primary Sodium Leak Event in FBTR," IGC Newsletter, January 2003.

11. To put that in perspective, the allowed dose for nuclear workers in an average year is 20 mSv. So in 1.3 minutes, a worker could be exposed to the maximum permitted annual dose.

12. Sasikumar, Krishnamachari, and Ramalingam, "Primary Sodium Leak Event in FBTR."

13. K. V. Suresh Kumar et al., "Fast Breeder Test Reactor. 15 Years of Operating Experience" (paper presented at the Technical Meeting on Operational and Decommissioning Experience with Fast Reactors, Cadarache, March 11–15 2002).

14. R. Prasad, "India: FBTR Passes 53-Day Continuous Operation Test," *The Hindu*, 22 March 2001.

15. DAE, "Atomic Energy in India: A Perspective" (Mumbai: Department of Atomic Energy, Government of India, 2006).

16. Placid Rodriguez, "The Past Is the Springboard to the Future," IGC Newsletter, October 2000.

17. Praful Bidwai, "The Fast Breeder Reactor: DAE's Strange Nuclear Priorities," *The Times of India*, 31 August 1983.

18. DAE, "Performance Budget 1990–91" (Mumbai: Department of Atomic Energy, 1991).

19. Mark Hibbs, "India's New Breeder Will Be on Line by 2000, Iyengar Says," *Nucleonics Week* 31(42) (1990).

20. T. S. Subramanian, "A Milestone at Kalpakkam," *Frontline*, 19 November 2004.

21. Ashwin Kumar and M. V. Ramana, "Compromising Safety: Design Choices and Severe Accident Possibilities in India's Prototype Fast Breeder Reactor," *Science and Global Security 16* (2008).

22. A reduction of coolant density has three effects. The reduced coolant absorbs fewer neutrons, the mean energy of neutrons is higher, and there is more leakage. In a fast reactor, higher neutron energy results in more Pu-239 fissions and therefore the first two effects increase reactivity. Leakage effects are important only near the periphery of the core, and therefore become less important as a whole as the volume of the core increases.

23. IAEA, "Fast Reactor Database: 2006 Update" (Vienna: International Atomic Energy Agency, 2006). A "dollar" is the margin of reactivity provided by delayed neutrons, which are typically released only after tens of seconds. If the reactivity increases above unity by more than this amount, the rate of power increase is controlled by the much shorter generation time (about 10 microseconds) of prompt neutrons.

24. S. C. Chetal et al., "The Design of the Prototype Fast Breeder Reactor," *Nuclear Engineering and Design* 236 (2006).

25. The numerator is a measure of the ability of the containment to withstand an accident. The choice of the denominator stems from the expectation that the energy that would potentially be released during an accident would be very roughly proportional to the power rating of the reactor.

26. APS Study Group, "Radionuclide Release from Severe Accidents at Nuclear Power Plants," *Reviews of Modern Physics* 57(3) (1985).

27. Chetal et al., "The Design of the Prototype Fast Breeder Reactor."

28. Karl Wirtz, *Lectures on Fast Reactors* (La Grange Park, IL: American Nuclear Society, 1978).

29. Om Pal Singh and R. Harish, "Energetics of Core Disruptive Accident for Different Fuels for a Medium Sized Fast Reactor," *Annals of Nuclear Energy* 29 (2002).

30. V. Badham and C. K. Chan, "A Look at Alternative Core-Disruptive Accidents in LMFBRs—Part II: Neutronic and Fuel Element Behavior," *Nuclear Engineering and Design* 55 (1979), J. F. Jackson and R. B. Nicholson, "Venus-II: An LMFBR Disassembly Program" (Argonne, IL: Applied Physics Division, Argonne National Laboratory, 1972), KAERI, "Review of Core Disruptive Accident Analysis for Liquid-Metal Cooled Fast Reactors" (Korea Atomic Energy Research Institute, 1997), T.G. Theofanous and C.R. Bell, "Assessment of CRBR Core Disruptive Accident Energetics" (Los Alamos National Laboratory, 1984).

31. Georges Berthoud, "Vapor Explosions," *Annual Review of Fluid Mechanics* 32 (2000).

32. Singh and Harish, "Energetics of Core Disruptive Accident for Different Fuels for a Medium Sized Fast Reactor."

33. Kumar and Ramana, "Compromising Safety: Design Choices and Severe Accident Possibilities in India's Prototype Fast Breeder Reactor."

34. Anil Kakodkar, "Securing Our Emerging Energy Needs: What Nuclear Energy Can Do," *Energy Security Insights* 1 (1) (2006).

35. J. Y. Suchitra and M. V. Ramana, "The Costs of Power: Plutonium and the Economics of India's Prototype Fast Breeder Reactor," (submitted).

36. Though the units constructed so far have been of smaller capacity, according to the DAE, "future PHWRs, beyond those under construction, are planned to be only of 700 MW unit size." See DAE, "Annual Report 2004–2005," (Mumbai: Department of Atomic Energy, 2005). Four such 700 MW reactors are at an advanced state of planning and early procurement of equipment has started. See DAE, "Annual Report 2007–08," (Mumbai: Department of Atomic Energy, 2008).

37. Matthew Bunn et al., "The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel," (Cambridge: Harvard University, 2003). One reason for the increased cost is that breeder reactors such as the PFBR use molten sodium as coolant. This brings with it several operational requirements, such as heating systems to keep the sodium molten at all times, and safety related requirements, such as extensive fire fighting equipment. See A. A. Farmer, "Assessing the Economics of the Liquid Metal Fast Breeder Reactor," in *The Economics of Nuclear Energy*, ed. Leonard G. Brookes and Homa Motamen (London: Chapman and Hall, 1984).

38. NEA, "Accelerator-Driven Systems (Ads) and Fast Reactors (Fr) in Advanced Nuclear Fuel Cycles" (Paris: Nuclear Energy Agency, OECD, 2002).

39. IGCAR, Design of Prototype Fast Breeder Reactor (Indira Gandhi Centre for Atomic Research, 2003 [cited 10 March 2006]); available from www.igcar.ernet.in/broucher/design.pdf.

40. Alexander Glaser and M V Ramana, "Weapon-Grade Plutonium Production Potential in the Indian Prototype Fast Breeder Reactor," *Science and Global Security* 15 (2007).

41. M. V. Ramana and J. Y. Suchitra, "Costing Plutonium: Economics of Reprocessing in India," *International Journal of Global Energy* 27(4) (2007).

42. Suchitra and Ramana, "The Costs of Power: Plutonium and the Economics of India's Prototype Fast Breeder Reactor."

43. NEA, "Accelerator-Driven Systems (Ads) and Fast Reactors (Fr) in Advanced Nuclear Fuel Cycles."

44. Suchitra and Ramana, "The Costs of Power: Plutonium and the Economics of India's Prototype Fast Breeder Reactor."

45. Chetal et al., "The Design of the Prototype Fast Breeder Reactor."

46. Kenneth S. Deffeyes and Ian D. MacGregor, "World Uranium Resources," *Scientific American*, January 1980.

47. Eric Schneider and William C. Sailor, "Long Term Uranium Supply Issues and Estimates" (Washington, D.C.: Los Alamos National Laboratory, U.S. Department of Energy, 2005).

48. Zia Mian et al., "Fissile Materials in South Asia: The Implications of the U.S.-India Nuclear Deal" (International Panel on Fissile Materials, 2006).

49. Pallava Bagla, "On the Record: Anil Kakodkar" *Indian Express*, 8 February 2006.

50. Glaser and Ramana, "Weapon-Grade Plutonium Production Potential in the Indian Prototype Fast Breeder Reactor."

51. R. B. Grover and Subash Chandra, "Scenario for Growth of Electricity in India" *Energy Policy* 34(17) (2006), M. R. Srinivasan, R. B. Grover, and S. A. Bhardwaj, "Nuclear Power in India: Winds of Change," *Economic and Political Weekly* 40 (49) (2005).

52. The increased breeding ratio comes with a safety penalty because metal fuelled reactor cores will have even higher sodium void coefficients. See A. Riyas and P. Mohanakrishnan, "Studies on Physics Parameters of Metal (U-Pu-Zr) Fuelled FBR Cores," *Annals of Nuclear Energy* 35 (1) (2008).

53. Grover and Chandra, "Scenario for Growth of Electricity in India."

54. M. V. Ramana and J. Y. Suchitra, "Slow and Stunted: Plutonium Accounting and the Growth of Fast Breeder Reactors in India" (Submitted).

55. *Ibid.*