The Limits of Safety Analysis: Severe Nuclear Accident Possibilities at the PFBR

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The Prototype Fast Breeder Reactor that is being built in Kalpakkam in Tamil Nadu has the potential to undergo severe accidents that involve the disassembly of the reactor core. Such accidents could release sufficient energy to fracture the protective barriers around the core, including the containment building, and release large fractions of the radioactive material in the reactor into the surroundings. The designers of the PFBR have made choices aimed at making the reactor cheaper rather than safer. The safety assessment of the PFBR points to some fundamental problems with how nuclear technology is regulated.

In September 2011, the director of the Indira Gandhi Centre for Atomic Research (IGCAR) announced that the centre had finalised the design of commercial fast breeder reactors to be built at Kalpakkam (Tamil Nadu) and elsewhere (PPI 2011). This design is reportedly modified from that of the Prototype Fast Breeder Reactor (PFBR), also being built in Kalpakkam, with an eye towards lowering the cost of construction. This should be of concern because even the PFBR is unsafe by being unprotected against severe accidents, despite assurances to the contrary offered by the nuclear establishment (Subramanian 2011). The main problem with the PFBR is that its containment design does not protect adequately against severe accidents that can occur. Furthermore, design choices made by the ICGAR at Kalpakkam have made such accidents more likely and also potentially more destructive. Equally troubling is the inadequacy of the safety analyses performed by the ICGAR, which bases its analyses on optimistic assumptions about the conditions prevailing in the reactor during a severe accident. Because the PFBR is to be the first of many of its kind, the ICGAR’s design of this reactor is likely to influence subsequent developments.

The reasons for the above assertions have been discussed at length in our 2008 article published in the journal Science and Global Security (Kumar and Ramana 2008). In response to this article and to a subsequent summary article by us in the Bulletin of the Atomic Scientists (Kumar and Ramana 2009), Baldev Raj, former director of the ICGAR, wrote a letter in Science and Global Security seeking to rebut our assertions (Raj 2009). Although we welcomed the response, it did not address the issues we raised. Our counter-response describes what the ICGAR’s response lacked (Kumar and Ramana 2009). ICGAR did not respond to our counter-response, and in essence ignored it. Indeed, when a prominent columnist wrote an article in the Times of India in March 2011 in the context of the then ongoing Fukushima accidents pointing out that there are even greater safety concerns about fast reactors, the Nuclear Power Corporation (NPC) put up an article by Baldev Raj and Prabhat Kumar on its website that simply reiterated some of the points made in Baldev Raj’s response without seeking to engage our arguments (NPC 2011). It did not even mention that we had refuted these points.

In this article we discuss the potential for severe accidents at the PFBR and lacunae in its design, as well as problems with ICGAR’s safety analyses. We also attempt to deliberate on the implications for nuclear safety in general. We start with an overview of the accident hazards involved in fast breeder reactors.

Physics of Fast Breeder Reactors

For decades, the Department of Atomic Energy (DAE) has been committed to the development of fast breeder reactors, which can produce more fuel than they consume. The DAE’s main argument is that India has limited reserves of uranium ore, thereby necessitating the construction of breeder reactors that are more efficient in the use of uranium. While attractive in terms of uranium utilisation, breeder reactors are expensive, even more so than common thermal reactors, and pose risks of severe accidents. Herein, we describe only the latter concern.

All nuclear reactors contain a core whose key components are its “fissile materials”. These materials absorb neutrons and undergo fission, i.e., split into two or more lighter nuclei, releasing energy and additional neutrons. Broadly speaking, one can classify reactors into two: thermal and fast. In thermal reactors, the neutrons released during fission are slowed down by including some light material like water or heavy water or graphite in the core. When the neutrons interact with these materials, they lose energy and become...
slower, i.e., they thermalise. In fast reactors, as the name implies, there is no such light material to slow down the neutrons and they remain fast and energetic till they interact with another fissionable nucleus or they escape from the core. Of course, there is some slowing down of neutrons in all reactors because of collisions with the coolant that is necessary for carrying away the heat from the reaction.)

In some reactors, those neutrons that are escaping the core are captured by a blanket made of “fertile materials”, which then eventually get transformed into a new element that is itself fissile, i.e., it can be used as a fuel in a reactor core. An example of such a fertile material is uranium-238, which gets converted into a fissile isotope of plutonium, plutonium-239. Uranium-238 is the most common isotope of uranium, constituting about 99.3% of naturally available uranium.

Thus, in effect, a breeder reactor is one that produces more fissile material in its blankets than is consumed in its core. A system of breeder reactors is indirectly fuelled by uranium-238, which is much more abundant than the lighter isotope uranium-235 fuelling most thermal reactors. This allows a much larger capacity of nuclear power to be built using breeder reactors, based on the same resource of uranium ore.

Safety Consequences: The Core Disassembly Accident

Operating a nuclear reactor using fast neutrons has far-reaching consequences for safety. In thermal reactors, the core is typically in its most reactive configuration when it is operating normally at full power. Any change to this configuration in an accident would therefore decrease the power being produced. For example if the fuel is dispersed, neutrons escape from the core without inducing further fissions and this causes the power to decrease. Instead if the fuel is collapsed into a smaller volume, the resulting decrease in moderation of neutrons makes their energies less suitable for fission and consequently reduces the power.

In fast reactors by contrast, collapsing the fuel into a reduced volume increases the rate at which the chain reaction occurs. If this were to happen quickly enough, the pressure in the fuel would rise fast enough to lead to an explosion. This could fracture the protective barriers around the core, including the containment building, and release large fractions of the radioactive material in the reactor into the surroundings. Such a “core disassembly accident” (CDA) has therefore been an important concern among the fast reactor design community ever since the first fast neutron reactors were constructed.

The calculation of energy releases in CDAs has also been an important aspect of regulating the safety of fast reactor designs. The first calculation of the energy released by core disassembly was carried out by the Nobel Prize winning physicist H A Bethe along with J H Tait (Bethe and Tait 1956). Since then, CDA studies have been conducted for nearly all of the FBRS constructed or proposed in the United States and western Europe (Wilson 1977).

Effect of a Positive Coolant Void Coefficient

In some fast reactor designs, properties of the coolant and core design make matters worse. If in an accident the coolant were to heat up and expand there would be fewer collisions between the coolant and the neutrons so that the latter on average become faster. In fast reactors, faster neutrons increase the power generated in the reactor core. A decrease in coolant density also allows more neutrons to escape the core. The net effect depends on the size of the core. In larger reactors, the second effect becomes less important so that they have a stronger coolant void effect. In thermal reactors by contrast, faster neutrons slow down the reaction because these are less efficient at producing fissions. The larger the magnitude of the destabilising coolant void effect (measured by the “coolant void coefficient” – positive quantities implying that the reaction rate increases with the temperature of the coolant), the more likely that an accident that begins via a heating of the coolant can spread to large parts of the core.

Fast reactors are not the only type of reactors where a positive coolant void coefficient could play a role in an accident. Indeed, the best known event where the reactor demonstrated such behaviour was during the 1986 Chernobyl accident.

Though the dangers stemming from a positive coolant void coefficient have been recognised for long, it is especially after Chernobyl that reactor designers have by and large tried to move away from designs that have this feature. However, the DAE has chosen to design the PFBR with a large and positive coolant void coefficient (IAEA 2006).

This is quite different from the Fast Breeder Test Reactor (FBTR) in Kalpakkam, which is much smaller and as a result contains much less fissile material. Moreover, owing to its small size, the coolant void effect for the FBTR is negative, i.e., stabilising, and will not lead to a runaway power increase. Therefore, it does not offer a test-bed for the types of safety challenges that the PFBR is likely to pose. Therefore, the PFBR is unprecedented in the DAE’s experience.

Safety in India’s PFBR

To designers of nuclear reactors, safety is achieved by what is frequently called “defence-in-depth”, involving the design of backup components and systems that prevent escalation of accidents (for example, coolant pumps), devices that seek to restore the system to a relatively safe state (such as multiple shutdown systems), and physical barriers against the release of radioactive material into the environment (for example, the reactor vessel and containment building). Safety is a claim about future operation, so understanding whether a reactor is safe requires knowledge of what situations must be protected against. Quite often, real accident possibilities are ignored. To give a recent example, designers of the Fukushima nuclear power plant had not allowed for the possibility of a large tsunami wave drowning the backup power supplies.

In addition, there are sometimes gaps in knowledge about the consequences of initial events. This is inevitably the case with the understanding of what goes on inside the core of a reactor during a severe accident in which the fuel has melted, because the processes then become difficult to describe completely using mathematical models. This poses a problem in fast breeder reactors, where the consequences of CDAs are very sensitive to assumptions.
The PFBR Containment Design

One way to deal with the sensitivity to assumptions and the possibility of a larger-than-expected accident is to build structures around the reactor that would contain the effects of such an accident and prevent the release of radioactivity into the biosphere. The design of the protective barriers for the PFBR is based on assuming that a worst-case core disruptive accident would release an explosive energy of 100 megajoules (MJ, or a million joules), which in turn is based on the assumption that only about half the core participates in the CDA (Singh and Harish 2002). However, this 100 MJ value is small in comparison to other fast reactor designs.

A reactor that can produce more power in its core while operating normally contains more fissile material, and therefore reactors producing more power can release more energy in a CDA. The PFBR is designed to produce more power than most fast breeder reactors developed in other countries, yet its containment design is weaker than these reactors. One measure of the conservativeness of a reactor designed for a CDA, relative to its size, is the ratio of two quantities: firstly, the explosive energy that it is designed for and, secondly, its maximum thermal power. For the PFBR, the thermal power is 1,200 MW and the maximum CDA energy is assumed to be 100 MJ, and so this ratio is about 0.08. In contrast, the SNR-300 reactor that was constructed (but never operated due to safety concerns) in Germany had a ratio of about 0.5: it was designed to contain 370 MJ of explosive energy, although it had a much smaller core that could produce 760 MW of thermal power (Walter and Reynolds 1981). In this sense, the PFBR containment is much weaker than other fast reactors (Kumar and Ramana 2008). IGCAR’s only response was that the PFBR’s value of 0.08 is still only about half the core participates in the CDA (Singh and Harish 2002). However, this 100 MJ value is small in comparison to other fast reactor designs.

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Key Assumptions on Low Energy Release

IGCAR obtains its 100 MJ value for the maximum possible energy release through two crucial assumptions: that only about half the core can melt and collapse in a CDA, and that only 1% of the thermal energy is converted to mechanical work (Singh and Harish 2002). Not only are both these assumptions doubtful, but the consequences for the containment are also very sensitive to them. It is obviously inadvisable to stage empirical tests of what might go wrong in a reactor when the safety systems fail. Therefore, designers must rely on mathematical models. To calculate what happens immediately after an accident, and how the fuel and coolant are affected over time, IGCAR uses an internally developed model. This is a difficult enterprise because of the many processes involved, each of which is difficult to represent especially when the fuel is melting as in a CDA and consequently the geometry of the core is changing rapidly. All of these factors make the results of such models uncertain (Bell 1981).

Using its model, the DAE estimates that following an accident in which the coolant pumps fail so that liquid sodium stops circulating within the core, at most about half the core can melt (Singh and Harish 2002). One might consider basing containment design on such a result if we can be very confident in this assumption about how much of the core is involved, or alternatively if the outcome is shown to be insensitive to changing assumptions. Neither is true. The energy released in a CDA depends strongly on how much of the core collapses, and there are omissions in the analysis that might make the accident worse. Broadly they involve ignored physical process or changes to the fuel as they are irradiated and that could accelerate the progression of an accident.

In addition, small-scale experiments that have attempted to reproduce selective phenomena in this accident situation have found that as much as 4% of the thermal energy might be converted into mechanical energy, much higher than the 1% conversion efficiency that IGCAR assumes (Berthoud 2000). In reactor safety calculations in France for the PHENIX and in the United States for the Fast Flux Test Facility (FFTF), efficiencies of 5-10% have been used (Wilson 1977). While we pointed out this uncertainty in our original paper, IGCAR never addressed this issue in its response. To our knowledge, IGCAR has not tried to conduct any reliable experiments on the efficiency of thermal to mechanical energy transfer, a crucial determinant of the destructiveness of CDAs.

Even at the lower level of conversion efficiency, IGCAR’s own studies of the PFBR show that energies on the order of 1,000 MJ are possible under some circumstances (Singh and Harish 2002). Our own calculations also show that under easily conceivable severe accidents, the resulting pressure on the containment structure would be much higher than what it is designed for. If this were to occur, the containment’s integrity would be compromised leading to the escape of radioactivity into the surroundings.

The Response

In his letter published in Science and Global Security, Baldev Raj simply dismisses concerns about a positive void coefficient, mainly using the argument that there are multiple features of the design that “prevent” situations where coolant boiling would occur (Raj 2009). This is certainly not the case, as we describe further.

In his letter, Raj correctly points out that the improved treatment of some physical processes has led to a decrease in the estimated mechanical energy release over time. This is indeed the case, and contributed partly to a decrease in the ratio of explosive energy to thermal power over time. However, as we describe in our article (Kumar and Ramana 2008) there is no reason that this ratio should fall below its value in the previous batch of fast reactors designed in the 1970s and 1980s.
whose accident studies already considered these processes. A comparison of the PFBR with the reactors designed during this period is unfavourable, because it is designed for a much smaller ratio of explosive energy to thermal power than these reactors.

Raj also offered the suggestion that safety studies of the PFBR have shown that the mechanical energy release from the worst-case accident, involving a loss of coolant followed by a failure of the safety systems is less than 1 MJ. This contradicts IGCAR’s own studies of the PFBR showing that energies of the order of 1,000 MJ are possible, and that too with the assumption of a small thermal to mechanical energy conversion efficiency. Other such claims can be shown to be unjustified by IGCAR’s own studies. More recently, the response posted on the NPC website has restated the claims that the PFBR is safe (NPC 2011). However, like its predecessor it does not show how a containment that is designed to withstand only 100 MJ of energy release can be considered safe. Instead, it offers the red herring that the basis for designing the containment structure in fast breeders is different from that of pressured heavy water reactors because in the former the coolant is not at high pressure. This is no doubt true, but the important question is whether the design pressure in the PFBR containment is large enough to withstand a CDA. Because IGCAR’s safety studies severely underestimate the magnitude of energy that can be released in a CDA, they underestimate how much of the sodium coolant can be expelled to the containment and consequently the pressure rise in the containment from the burning of this sodium (sodium burns in air; therefore, coolant expelled from the reactor vessel to the containment building in an accident will catch fire and increase the pressure in the containment).

The response posted on the NPC website also displays two tactics often used by the nuclear establishment when faced with criticism. The first is to make extravagant claims about the subject of the criticism, in this case, claims about how safe the PFBR is, without actually engaging with the problems highlighted. To the uninitiated, this may seem very impressive, but this is in essence a diversionary tactic. Even more of a diversion is the second tactic – to make claims about how important nuclear power is to India and the sheer necessity of deploying breeder reactors, regardless of whether they are unsafe or uneconomical or otherwise undesirable. Again, this tactic renders impossible any reasoned debate about specific characteristics of a nuclear reactor or project.

**Overconfidence**

Why do the IGCAR’s safety studies make these choices about the course of an accident? Part of the reason appears to be overconfidence on the part of at least some designers. As one former IGCAR official has argued, the fast reactor community “ought to assert themselves and destroy the sodium void phobia… the necessity of a dome on the top of the reactor vessel and the core catchers needs to be challenged…after all, if the reactor can be designed to be inherently safe or if the probability of failure of the shutdown function can be brought to 1 in 108 per demand, why invest more funds for safety features” (Paranjpe 1992). This conviction that the reactor is inherently safe comes in the way of reliable safety studies and is manifested partly through assumptions that cannot really be reasonably considered representative of a really severe accident. Here too, there appears to be an effort at using probabilistic analysis to justify safety, without regard to the consequences. However, the evidence from IGCAR’s own studies suggests otherwise, that sodium voiding is not an irrational phobia. It might be managed if its effects are thoroughly understood. Unfortunately, the accident studies of the PFBR have not thoroughly examined its effects.

The nuclear establishment has continued to reiterate its arguments for the benign sodium void effect and furthermore claimed that in an accident when there is a loss of power to the coolant pumps the decay heat can be removed by natural circulation of the coolant once the reactor has been shut down (NPC 2011). This claim is refuted by IGCAR’s own studies of the progression of an accident in which power to the coolant pumps are lost, which show that boiling of the coolant can occur. Moreover, this says nothing about a situation in which the reactor is not successfully shut down.

The overconfidence displayed by IGCAR is typical of the DAE and its attendant organisations, which seem completely confident that the facilities that they build and operate are safe. For example, the chairman of the Atomic Energy Commission asserted in the aftermath of Fukushima that nuclear reactors [in India] are “one hundred per cent” safe. This confident view of safety is not just a public position but deeply internalised. In fact, the former chairman of the NPC has stated that it is “important” that “the people (operating the nuclear plant) should be confident about safety” (Subramanian 2000). Such overconfidence goes against recommendations by researchers studying safety culture in organisations (Reason 2000).

This overconfidence is compounded by a failure of the regulatory process, which clearly has overlooked the flaws in IGCAR’s studies of the safety of the PFBR. This could be because of neglect, and also because of inadequate powers of oversight. This is illustrated by the fact that despite the Atomic Energy Regulatory Board (AERB) recommending that the pressure that the containment is designed to withstand “should not be less than 30 kPa” (AERB 2003: 12), IGCAR chose a design pressure of 25 kPa (Chetal et al 2006). Many of the AERB’s safety evaluation committees are constituted by personnel from the DAE and associated organisations (Gopalakrishnan 1999), and this is likely to compromise their independence. Some years after the AERB cleared the PFBR for construction, one of the authors of the IGCAR’s studies of the energetics of a CDA at the PFBR became the secretary of the AERB.

**Choices Not Made**

This overconfidence in the safety of the reactor might have affected the IGCAR’s decision to not choose an alternate design that would decrease the magnitude of the positive coolant void coefficient. It is possible to decrease this effect by designing the reactor core so that fuel sub-assemblies are interspersed within the depleted uranium blanket, in what is termed a heterogeneous core. The Clinch River Breeder Reactor, which was
eventually cancelled, was designed with a heterogeneous core, and Russia has explored a heterogeneous core for its planned BN-1,600 reactor (Walter and Reynolds 1981; Troyanov et al 1990). Such a core is like having many smaller cores. As described earlier, a small core has a smaller sodium void effect due to leakage; in a heterogeneous core, the reduced sodium void effect is due to the increased neutron absorption by nearby blankets. But this will require a larger amount of fissile material in the core.

Economics, not safety, has possibly played an important role in the choice of PFBR design. The nuclear establishment has argued that imposing the economic cost of a higher fissile material inventory is not justified (Paranjpe 1992). The choice of containment design also appears to be directly linked to cost reduction efforts made in the 1990s (Bhoje 2001). The nuclear establishment has emphasised that “minimising capital cost” was one of the design objectives for the PFBR as it “would be the head of a series of at least a few reactors” (Bhoje 2002). It has also asserted that “the capital cost of FBRs will remain the most important hurdle” to rapid deployment of breeder reactors (Paranjpe 1991).

The irony is that this unsafe breeder reactor is still too expensive, with unit electricity costs being about 50% to 80% more expensive than corresponding costs from the DAE’s heavy water reactors (Suchitra and Ramana 2011). And this is with the original cost estimates, before applying the roughly 60% cost increases that have been reported.

Broadly speaking, there were two possibilities for the PFBR’s design. One possibility was to design a fast reactor that could meet safety norms that are more widely agreeable, for example, with a negative void coefficient and a containment structure that can withstand somewhat severe accidents. However, this would have made the reactor even more expensive than it is, and thus completely undermine the already poor economic rationale for the project.

The second possibility was to design the PFBR based on multiple constraints that work sometimes at cross purposes, including cost, plutonium breeding rate, manufacturing capabilities, and then initiate safety studies designed to show that the reactor is “safe”. This is evidently what the nuclear establishment has done, and its assumptions about the “maximum energy release” are really a statement not about some fundamental physical or technical constraint restricting the size of the severity of a CDA but about what its design, chosen on the basis of economic and other considerations, can be suggested to withstand.

Towards More Responsive Public Engagement

The nuclear establishment’s repeated inability to engage substantively with any questions raised about its programmes suggests that it is probably a victim of its own rhetoric at the highest levels of the organisation. This is despite what are undoubtedly good intentions among individual
employees of the organisation, and does not bode well for safety. Researchers who study how some organisations operating high-risk technologies manage to do so without failures find that, among other characteristics, these organisations continuously seek improvement. They are definitely not overconfident and are always looking to explore what could go wrong and how potential problems might be solved.

In the case of the PFBR, the situation is more urgent. There is direct evidence, including from IGCAR’s own studies, that the containment design is not adequately safe. The difficulty started when the organisation committed itself to making fast breeder reactors such an integral part of its programme, notwithstanding the possibility of core disassembly accidents. In this aspect, the Indian case is not unique and other developers of fast reactors have previously faced similar challenges. The Indian case is different in two respects. First, the PFBR was designed by making more optimistic assumptions about the energy release in a core disassembly accident than other fast reactors. Second, the PFBR is meant to be the first of many of its kind. In a nuclear programme that is slated to expand rapidly, the consequences are too large to ignore. In designing a PFBR that is feasible to build, the nuclear establishment has imposed risks on the public that it has so far not acknowledged. The interests of democracy will be served by making this transparent.

The case of the PFBR is different in another aspect. In many countries that initially pursued breeder reactors, top policymakers were rightly sceptical of the breeder reactor community and its claims about either the safety or the economics of breeder reactors. The DAE is among the few institutions that is both committed to a breeder programme and enjoys the confidence of its national policymakers.

Fundamental Problems

The safety assessment of the PFBR points to some fundamental problems with how nuclear technology is regulated, and these problems are accentuated by the conditions in India. Knowledge about nuclear technology is available to few, almost all of them associated with the nuclear establishment. The AERB was part of the same family. Recent measures to establish an independent regulator are welcome but in the end unlikely to fundamentally alter this state of affairs. Therefore, the incentive to conduct objective studies examining the safety capabilities of its designs is unlikely to emerge anytime soon. That makes it all the more important for the DAE’s claims of safety to be seen as trustworthy. For this to happen, the institution must engage with criticism, and demonstrate self-awareness, reflection and acknowledge that its claims can sometimes be wrong (Wyne 2006). If the DAE cannot show the criticism of the PFBR’s safety to be invalid, it is left with the choice of either arguing why the public should live with the risk of unprotected core disassembly accidents or making the next batch of fast breeder reactors safer. Thus far, the DAE has chosen not to engage with the public seriously on questions of nuclear safety, and, in its efforts to redesigning the breeder reactor design, appears to have focused on lowering costs rather than improving safety.

NOTES
1 This paper is available at http://www.princeton.edu/sgs/publications/sgs/archive/Kumar-and-Ramana-Vol-16-No-3.pdf
2 This article is available at http://www.thebulletin.org/web-edition/features/the-safety-inadequacies-of-indias-fast-breeder-reactor
3 This article is available at http://www.princeton.edu/sgs/publications/sgs/archive/17-2-3-Raj-letter-to-editor.pdf
4 This article is available at http://www.princeton.edu/sgs/publications/sgs/archive/17-2-3-Reply-Kumar-Ramana.pdf
5 We use the term explosion to mean a rapid release of energy. The mechanism behind such a release of energy is essentially the same as in a nuclear weapon explosion, though the energy releases are very much lower.
6 For perspective, 1 kilogram of TNT upon exploding releases approximately 4.2 MJ of energy.

REFERENCES