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The Indian Nuclear Industry: Status and Prospects

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Summary

In September 2008, the Nuclear Suppliers Group (NSG) offered a special waiver to India, exempting it from the nuclear export guidelines its members set for themselves. Under the terms of the waiver, usually referred to as the US-India deal, India was allowed to import nuclear reactors and other technology without becoming a party to the 1968 Nuclear Non-Proliferation Treaty (NPT). It was also allowed to import uranium for fueling those domestically constructed reactors that it put under international safeguards. This waiver has raised expectations of a tremendous increase in nuclear trade with India. To make sense of these expectations and the prospects for nuclear power in India, this report offers a historical overview and assessment of the Indian nuclear industry, including India's indigenous efforts and the role of foreign aid and expertise. The assessment points to some successes in India's nuclear energy program, but notes significant safety concerns, high costs, and a limited production of energy. The author concludes that nuclear energy will remain an important part of India's energy plan, but notes that even under the conditions of the waiver, its contribution will remain modest for decades to come.

Canadian Centre for Treaty Compliance

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CIGI's Nuclear Energy Futures Project

CIGI's Nuclear Energy Futures Project is chaired by CIGI distinguished fellow Louise Fréchette and directed by CIGI senior fellow Trevor Findlay, director of the Canadian Centre for Treaty Compliance at the Norman Paterson School of International Affairs, Carleton University, Ottawa. The project is researching the scope of the purported nuclear energy revival around the globe over the coming two decades and its implications for nuclear safety, security and nonproliferation. A major report to be published in 2009 will advance recommendations for strengthening global governance in the nuclear field for consideration by Canada and the international community. This series of papers presents research commissioned by the project from experts in nuclear energy or nuclear global governance. The resulting research will be used as intellectual ballast for the project report.

We encourage your analysis and commentary and welcome your thoughts. Please visit us online at www.cigionline.org to learn more about the Nuclear Energy Futures Project and CIGI's other research programs.

List of Acronyms

AEC	Atomic Energy Commission
AECL	Atomic Energy Canada Limited
AERB	Atomic Energy Regulatory Board
BARC	Bhabha Atomic Research Centre
BARCCIS	Bhabha Atomic Research Centre Channel Inspection System
BFEA	BARC Facilities Employees Association
BHAVINI	Bharatiya Nabhikiya Vidyut Nigam
BHEL	Bharat Heavy Electricals Limited
CAG	Comptroller and Auditor General
CANDU	Canadian Deuterium Uranium
CDA	Core Disruptive Accident
CIR	Canada India Reactor (subsequently renamed CIRUS)
DAE	Department of Atomic Energy
EAR	Estimated Additional Resources
EIA	Environmental Impact Assessment
ECCS	Emergency Core Cooling System
FBTR	Fast Breeder Test Reactor
GW	Gigawatts
HLW	High Level Wastes
IAEA	International Atomic Energy Agency
ILW	Intermediate Level Wastes
IR	Inferred Resources
KARP	Kalpakkam Atomic Reprocessing Plant
kPa	Kilopascals
LLW	Low Level Waste
MAPS	Madras Atomic Power Station
MECO	Montreal Engineering Company
MJ	Megajoules
MOX	Mixed Oxide Fuel
MW	Mega Watts
NAPS	Narora Atomic Power Station
NPC	Nuclear Power Corporation
NPT	Nuclear Non Proliferation Treaty
NSG	Nuclear Suppliers Group
PFBR	Prototype Fast Breeder Reactor
PHWR	Pressurized Heavy Water Reactor
RAPS	Rajasthan Atomic Power Station
RAR	Reasonably Assured Resources
S3F	Solid Storage & Surveillance Facility
UKAEA	United Kingdom Atomic Energy Authority
WGEP	Working Group on Energy Policy

Introduction

In September 2008, the Nuclear Suppliers Group (NSG) offered a special waiver to India, exempting it from the nuclear export guidelines its members set for themselves. Under the terms of the waiver, usually referred to as the US-India deal, India was allowed to import nuclear reactors and other technology without becoming a party to the 1968 Nuclear Non-Proliferation Treaty (NPT). It was also allowed to import uranium for fueling those domestically constructed reactors that it put under international safeguards. This waiver has raised expectations of a tremendous increase in nuclear trade with India. To make sense of these expectations and the prospects for nuclear power in India, this report offers a historical overview and assessment of the Indian nuclear industry.

Like the NSG waiver, India's nuclear trajectory has also been largely unique. Ever since the country became independent, its political leadership and technological bureaucracy have been committed to a future where nuclear power plays a big role. Though these plans have not materialized, even six decades since their inception, hopes of a large expansion of nuclear power still abound. The most noteworthy successes of the program have been the acquisition by the Department of Atomic Energy (DAE) of expertise pertaining to the entire nuclear fuel "chain,"[1] from uranium mining and milling to reprocessing spent nuclear fuel, and vitrifying and storing waste (Sundaram, Krishnan and Iyengar, 1998). But the program has been marred by various accidents and evidence of poor safety practices. As elsewhere, nuclear electricity has been expensive, a greater problem in a developing country with multiple requirements for scarce capital.

India is also unique in that the proposed nuclear expansion is based on fast breeder reactors.[2] While many countries were initially enthusiastic about breeder reactors, most have given up on them (Von Hippel and Jones, 1997; IPFM, forthcoming). On the other hand, the DAE has displayed remarkable — though perhaps misguided — persistence, in part because of a shortage of domestic supplies of cheap and easily mined uranium.[3]

This report begins with a history of the Indian nuclear program, focusing on the role played by aid from other countries, the impact of the trade restrictions imposed after the 1974 nuclear test and their waiver as a result of the US-India nuclear deal, the organizational structure and system of regulation, and an account of the projections of nuclear power made in the past as compared to what was realized. The next section includes an analysis of the economics of nuclear power in India, followed by a section on the safety of nuclear facilities. Brief sections on waste management and public perceptions precede the final section on the future of nuclear power in India.

History

The Atomic Energy Commission (AEC), the apex body in charge of nuclear policy in India, was founded in 1948, soon after independence from Britain. The timing was a reflection of the high importance placed on nuclear energy by Jawaharlal Nehru, India's first prime minister, and the influence of a charismatic physicist, Homi Bhabha, who was the primary architect of the program. Bhabha had earlier set up a research institute to work on nuclear physics with funding from a trust established by the Tata industrial group.

The bill enabling the creation of the AEC was modeled after the *British Atomic Energy Act* and made atomic energy the exclusive responsibility of the state (Abraham, 1995).

Author Biography

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[1] The term "chain" is used here deliberately because the more common term "nuclear fuel cycle" carries with it the connotation of everything being used up eventually in a cyclical fashion, whereas in fact the nuclear energy production process inevitably creates large quantities of radioactive and other waste products, disposal of which remains a challenge.

[2] Fast breeder reactors are thus termed because they are based on energetic (fast) neutrons and because they produce (breed) more fissile material than they consume.

[3] Lack of uranium also provided an important motivation for the US-India nuclear deal.

But the act imposed even greater secrecy over research and development than did either the British or American atomic energy legislation (Perkovich, 1999: 18). In response to criticism of these secrecy provisions, given that atomic energy was purportedly to be pursued only for peaceful rather than military purposes, Nehru responded: "I do not know how to distinguish the two." Nehru's dilemma is clear from his statements while introducing the bill. On the one hand he said, "I think we must develop it for peaceful purposes." But he went on, "Of course, if we are compelled as a nation to use it for other purposes, possibly no pious sentiments will stop the nation from using it that way." Within the AEC itself, it was clear that the commission was created not only to generate nuclear electricity, but to develop "atomic energy for *all purposes*" (emphasis added) (Ramanna, 1991: 60). M. R. Srinivasan, who headed the AEC in the 1980s, explicitly states the commission's opinion: "[N]uclear technology was developed by a country to be solely available for its own benefit, whether for peaceful purposes or for military applications" (Srinivasan, 1997). This ability to use the technology for both military and peaceful purposes was an implicit criterion in many of the choices the AEC made over the coming decades. The AEC also claimed it wanted to achieve self-reliance, and so plans for the nuclear program, even at the very early stages, were ambitious and encompassed the entire nuclear fuel chain.

Six years after the AEC was established, it spawned the Department of Atomic Energy; Bhabha, as its head, became a secretary to the Government of India – the highest bureaucratic office in the system. The position of the DAE was further strengthened in 1962 when parliament adopted a revised *Atomic Energy Act* that tightened secrecy and the central government's control over all nuclear activities. What was significant, as Itty Abraham notes, was that, for the most part, neither the act nor the associated parliamentary debate referred to what was by then the customary focus on "peaceful uses" (Abraham, 1998: 114-120).

By that time the nuclear establishment had come up with a three-phase strategy for nuclear power in India as a way to build significant nuclear capacity despite relatively small amounts of uranium ore in the country (Bhabha and Prasad, 1958). The first phase involved using uranium fuel in heavy water reactors, followed by reprocessing the irradiated spent fuel to extract plutonium. In the second phase, the accumulated plutonium stockpile is used in the nuclear cores of fast breeder reactors. These nuclear cores could be surrounded by a so-called blanket of either depleted uranium or natural uranium to produce more plutonium; if the blanket was composed of thorium, it would produce uranium-233. So as to ensure that there was adequate plutonium to fuel these second-stage breeder reactors, a sufficiently large fleet of them would have to be commissioned before thorium blankets were introduced. The third phase involves breeder reactors using uranium-233 in their cores and thorium in their blankets.

Foreign Aid

Despite much rhetoric about self-reliance and indigenous development, the AEC sought and received ample help from other countries. Indeed, the next two decades until the nuclear test of 1974, were marked by India's acquisition of technologies related to the entire nuclear fuel chain from different countries.

Important among these technologies was the Canada-India Reactor (CIR), which later became known as the Canada-India Reactor US (CIRUS) when the United States supplied the heavy water for it. CIRUS was largely based on the design of the Canadian National Research Experimental (NRX) reactor. Financial assistance for the construction of the reactor was provided by Canada as part of the Commonwealth's Colombo Plan, a development assistance scheme "premised on the relation between misery and poverty and communism" (Bothwell, 1988). CIRUS produced the plutonium that was used in the 1974 nuclear test.

In addition to heavy water for CIRUS, the US was also the source of the technology used in the first reprocessing plant at Trombay, which separated plutonium from spent fuel rods irradiated at the CIRUS reactor. The design of the plant was based on the blueprints released by the US Atomic Energy Commission as part of the Atoms for Peace program. An American firm, Vitro International, was responsible for variations in the design used in Trombay (Wohlstetter, 1977: 3-61).

In 1959, the AEC turned to the United Kingdom's Atomic Energy Authority (UKAEA) for India's first power reactor (Parthasarathi, 2007: 12). The UKAEA promised to sell India a Gas Graphite Reactor, which uses natural uranium as fuel. When a global tender was put out, however, the UK had the highest bid, followed closely by France. The surprise winner was the US firm General Electric, whose bid for two 200 megawatt (MW) Boiling Water Reactors (BWR), which were to be fueled with enriched uranium, was half that of the UK. Though enriched uranium was not available in India and the stated policy at that time was to only construct natural uranium-fueled reactors, the pressure to generate cheap electricity trumped other considerations and General Electric began constructing two BWRs in Tarapur on the western coast.

In parallel, Bhabha also managed to work out a deal with Atomic Energy Canada Limited (AECL) and the Montreal Engineering Company (MECO) to construct a 200 MW Pressurized Heavy Water Reactor (PHWR, also known as CANDU for Canadian Deuterium Uranium). In April 1964, an agreement was signed between the Government of India and the Export Credit Insurance Corporation of Canada to cover financing of materials and services from AECL and MECO (Graham and Stevens, 1974: 23). The adopted design was identical to the one used for the first CANDU at Douglas Point in Ontario, Canada, even though no operational feedback from this reference reactor was available to the designers at that time (Gopalakrishnan, 2002). This proved a premature choice and resulted in many of the problems faced in some of the PHWRs subsequently built by DAE based on the CANDU. Part of the construction of a twin unit of the same design had been completed when the 1974 nuclear test was conducted; in response, Canada pulled out of that project and the reactor was completed by India only in April 1981.

In addition to water moderated reactors, the Indian AEC, like its counterparts in many other countries such as the United States, has always been greatly interested in fast breeder reactors, a central part of the three-phase strategy. In 1965, a fast reactor section was formed at the Bhabha Atomic Research Centre (BARC) and design work on a 10 MW experimental fast reactor was initiated (Bhoje, 2006). It soon became clear that external help was required. In 1969, the DAE entered a collaboration agreement with the French Atomic Energy Commission and obtained the design of France's Rapsodie test reactor and the steam generator design of its Phenix reactor (Rodriguez, 2004). This was to be the Fast Breeder Test Reactor (FBTR), India's first breeder reactor.

As part of the agreement, a team of approximately 30 engineers and scientists were trained at Cadarache, France. Once they returned, they formed the nucleus of the Reactor Research Centre (RRC) established in 1971 at Kalpakkam to lead the breeder effort (Rodriguez, 2004). In 1985, the RRC was renamed the Indira Gandhi Centre for Atomic Research (IGCAR).

Extensive foreign support for the Indian nuclear program ended only after the 1974 nuclear test. Canada and the US were incensed by India's use of plutonium from the CIRUS reactor given to India for purely peaceful purposes. India's attempt to portray the event as a peaceful nuclear explosion made little difference. These countries led the international community in establishing norms for exporting nuclear technology. Eventually these efforts resulted in the formation of the Nuclear Suppliers Group (NSG) with the aim of preventing exports for peaceful purposes from being used to make nuclear weapons. NSG guidelines list nuclear materials, equipment and technologies subject to export controls.

In addition, in 1978 the US Congress passed the Nuclear Non Proliferation Act that required any country, other than the five Nuclear Weapon States designated by the NPT, to accept International Atomic Energy Agency (IAEA) safeguards on all nuclear facilities ("full scope safeguards") before the US would engage in any nuclear cooperation with it. Safeguards are procedures to ensure that no fissile material (plutonium or enriched uranium) is diverted from peaceful purposes to make nuclear weapons. The Indian government's refusal to give up its nuclear weapons and put its nuclear facilities under safeguards meant that no NSG state, including the United States, would sell nuclear technology to it.

To some degree, the NSG restrictions achieved their desired effect. All nuclear facilities built in India since 1974 have taken longer to build and have been repeatedly scaled back. Replacement parts and equipment became harder to come by. The first reactors affected by the fallout of the 1974 test were those already under construction: the second unit of the Rajasthan Atomic Power Station (RAPS II) and the FBTR. Even with help from the Canadians, the first Rajasthan reactor, RAPS I, had been delayed. It was first projected to start operating in 1969 (Tomar, 1980), but was declared commercial only in December 1973 (Mittal, 2004). The fate of RAPS II was worse. RAPS II was originally supposed to come online in 1973, two years after RAPS I (DAE, 1969: 80), but was declared commercial only in April 1981 (Mittal, 2004).

The FBTR, based on the French Rapsodie reactor, was initially supposed to be ready for commission by 1976 (CAG, 1993). The reactor finally attained criticality only in October 1985. Its steam generator began operating in 1993 (Hibbs, 1997). Delays were also experienced in the PHWRs constructed by the DAE in the next two decades: the Madras and Narora Atomic Power Stations (MAPS & NAPS, respectively). MAPS and NAPS are located in the states of Tamil Nadu and Uttar Pradesh, respectively. As per the DAE's plans, MAPS I & II and NAPS I & II were to come online in successive years from 1975 through 1978 (AEC, 1970). The MAPS-I unit eventually began commercial operations in January 1984, and MAPS-II began in March 1986. The Narora units began operating in 1991 and 1992.

One reason for these delays was the unreasonable expectations of the capabilities of domestic industry, which was unable to manufacture some of the specialized equipment fast enough. The problem was not that the industry lacked the technological base and knowledge needed to carry out the fabrication, but that the DAE did not issue enough orders to make such manufacturing economical. Many businesses were therefore reluctant, and those that fulfilled the DAE's manufacturing orders did so at great expense. This was reflected in much higher costs for such equipment. For example, the turbo-generator for RAPS-I was imported from Canada for Rs. 64 million, whereas the same component for RAPS-II from a domestic manufacturer cost Rs. 130.4 million (Mirchandani and Namboodiri, 1981: 35).

Such delays must have been hard to swallow for many DAE scientists. To the extent possible, they have tried to put the best face on the situation. The DAE's leadership has tried to sustain the morale of personnel, as illustrated by BARC Director B. Bhattacharjee, in 2001, when he said:

> we are really comfortable when we work under sanctions. Our scientists and engineers enjoy working under sanctions because it acts as a catalyst for all of us, from the lowest level to the topmost level, to give our best. (Bhattacharjee, 2001)

At the same time, even before the NSG's recent removal of restrictions on nuclear trade with India, the embargo was not strictly followed and commercial or other institutional interests sometimes overrode non-proliferation considerations. One example is the Tarapur I & II reactors supplied by the US with a fuel supply guarantee; NSG members like France and Russia have also sold enriched uranium fuel (which the DAE does not have the capacity to manufacture in adequate quantities) for these reactors by using an exception clause — somewhat disingenuously — that allows for the sale of material or equipment if there are safety implications of not doing so. Likewise, Russia also started supplying the Koodankulam reactors by claiming the agreement governing that deal was signed in the 1980s by the Soviet Union before it joined the NSG. Apart from these noticeable instances, there were many cases when various nuclear facilities in India procured components from abroad and foreign consultants were hired for projects.

The delays imposed by the sanctions did not deter the DAE from making confident projections. In 1984, a decade after the controversial nuclear test, the DAE drew up a new atomic energy profile (CAG, 1999). It proposed constructing a number of 235 MW and 500 MW PHWR units so nuclear power generation capacity would reach 10,000 MW by 2000 (Ramanna, 1985). The results were even more shocking than India's previous history of constructing reactors might have indicated: not one of the proposed new reactors was constructed on time, despite expenditures in excess of Rs. 50 billion (CAG, 1999).

Projections and Achievements

The 1984 projection was just one in a long list made by the DAE. In 1962, it predicted that by 1987 nuclear energy would constitute 20,000 to 25,000 MW of installed electricity generation capacity (Hart, 1983: 61). This was subsequently updated to about 43,000 MW of nuclear power by 2000 (Sethna, 1972). In reality, installed capacity in 1979-80 was only about 600 MW, about 950 MW in 1987, and 2,720 MW in 2000. As of June 2009, nuclear power amounts to just 4,120 MW, roughly 2.8 percent of the country's total electricity generation capacity. Six reactors with a combined capacity of 3,160 MW are currently under construction.

Most of the operating reactors are 220 MW PHWRs, modified versions of the CANDU reactors India imported from Canada. Two 540 MW PHWRs, based on a scaled-up design, have been constructed. In the future, the DAE plans to build 700 MW reactors by modifying the same design to allow partial boiling of the coolant.

The largest component of the planned expansion consists of two Russian 1,000 MW VVER-1000 reactors, which are being constructed in Koodankulam, in the state of Tamil Nadu, close to Sri Lanka. The first industrial-scale breeder reactor, the 500 MW Prototype Fast Breeder Reactor (PFBR), based on mixed oxide (MOX) fuel, is also under construction at Kalpakkam.

Notwithstanding this less than modest history, the DAE continues to make wild claims about the contribution of nuclear power to the country's electricity generation capacity. In the early 2000s, the DAE projected 20 gigawatts (GW, or a 1000 MW) by the year 2020 and 275 GW by 2052; the latter figure amounts to 20 percent of India's total projected electricity generation capacity (Grover and Chandra, 2006). Following the September 2008 waiver from the Nuclear Suppliers Group, these estimates have gone up.[4] The AEC chairman has promised that nuclear power will contribute 35 percent of Indian electricity by 2050 (FE, 2008). Since the DAE has projected that India will have an installed electricity generation capacity of 1,300 GW (a nine-fold increase from the current 145 GW)

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[4] Over the last few years there have been a range of figures quoted for future nuclear power capacities in India and there seems to be no fixed "official" projection yet.

by that time, the 35 percent prediction implies that installed nuclear capacity would amount to 455 GW, more than 100 times today's figure. More recently, in September 2009, Prime Minister Manmohan Singh stated that India's nuclear capacity in 2050 could be 470 GW.

Budgets

The failure of the DAE to meet its projections cannot be attributed to lack of resources. Since its inception, it has received unstinted financial and political support from the government. Until the mid-1960s, the DAE cornered over a quarter of all resources devoted to science and technology development in the country (Hart, 1983: 62-64; Abraham, 1993: 177). This share declined somewhat by the 1970s because of the increased budget allotted to the space program. The only time the DAE did not get all for which it asked, which it considered "a period of total dryness and stagnation," was the early 1990s; the government's economic liberalization policies required spending cutbacks (Iype, 2000). But this trend was reversed with the 1998 nuclear weapons tests. Since then, the DAE's budget has increased from Rs. 19.96 billion in 1997-98 to Rs. 67.77 billion in 2008-09 (approximately US$0.5 billion and US$1.45 billion, respectively).[5] In comparison, the 2008-09 budget of the Renewable Energy Ministry, responsible for 13.88 GW of installed electrical capacity, was Rs. 5.09 billion.

Organizational Structure

The family of nuclear organizations in India is headed by the AEC. The AEC's role is to formulate policies and programs, while the actual execution of these policies is carried out by the Department of Atomic Energy (DAE). The DAE has in turn set up a number of associated or subsidiary organizations. These include five research centres, five government-owned companies ("public sector enterprises"), three industrial organizations and three service organizations. Among government-owned companies, the Nuclear Power Corporation (NPC) is responsible for designing, constructing and operating nuclear power plants in the first stage of the nuclear power program (breeder reactors are the responsibility of another government-owned company called BHAVINI, for Bharatiya Nabhikiya Vidyut Nigam). The government-owned Uranium Corporation of India Limited is in charge of mining and milling uranium. Industrial organizations, also owned by the government, include the Heavy Water Board, in charge of the many plants that produce heavy water, and the Nuclear Fuel Complex, which manufactures nuclear fuel. The best known research centres are the Bhabha Atomic Research Centre (BARC), the most important facility involved in nuclear weapons research, and IGCAR, where the breeder program was cultivated. Currently, these organizations comprise all players directly involved in the production and operation of nuclear reactors in India.

In contrast to most government institutions in the country, neither the AEC nor the DAE report to the cabinet and are answerable only to the prime minister. This structure makes it difficult for most politicians or bureaucrats, let alone the public, to challenge the DAE's policies or practices. The DAE also tries hard to maintain its position as the sole repository of nuclear expertise. The 1962 Atomic Energy Act vests in the DAE the power "to produce, develop, use and dispose of atomic energy…and carry out research into any matters connected therewith." Few academic institutions offer courses in nuclear engineering, and their graduates necessarily have to seek employment with the DAE. Therefore, the government is compelled to seek the DAE's advice on all nuclear matters.

The institutional structure in which the DAE operates allows it to effectively stonewall external appraisal. For example, the Comptroller and Auditor General (CAG), whose function is to enhance the accountability of various public sector organizations and departments to the parliament and state legislatures, has on many occasions not been able get the DAE to open its accounts for scrutiny (CAG, 1992, 1994). On one such unsuccessful occasion, when the CAG was trying to examine the costs of producing heavy water at the DAE's facilities, the DAE was reprimanded by the parliamentary Public Accounts Committee for its "disregard of accountability." But the DAE simply stated that: "Heavy Water being strategic material, it is not advisable to divulge information relating to its production and cost to functionaries at all levels" (Public Accounts Committee (1992-93), 1993). The DAE similarly explains away cost overruns. For example, in the case of the Manuguru Heavy Water Plant, the CAG found that the cost of the facility had increased by 133 percent; when questioned, the DAE stated that "the grounds for sanction of this project [were] strategic and not commercial" (CAG, 1994).[6]

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[5] The dollar to rupee exchange rate has varied significantly over the years. In October 1997, it was around Rs. 36/US$, whereas it exceeded Rs. 53/US$ in October 2008.

[6] Technically speaking, there is nothing more strategic (i.e., having military value) about heavy water than, say, coal. The only way by which heavy water production figures could provide information with strategic implications is if the reactors in the country involved in plutonium production for military purposes were facing a shortage of heavy water and therefore could not either be commissioned or function efficiently. The argument about strategic significance often does not have any basis in fact.

In addition, many official decision-making bodies that set policies which impinge on energy or security are obliged to include members of the nuclear establishment. For example, DAE officials are always a part of the various energy-related committees of government bodies such as the Planning Commission or the Central Electric Authority. Two reasons suggested are, first, that the DAE is considered the sole body "technically qualified" to decide nuclear policy issues and, second, there is a desire to avoid internal disputes among government bodies (Hart, 1983: 35).

It is therefore no surprise that reports by such committees fail to analyze either the performance of the DAE or its projections. Instead, they invariably extol the importance of nuclear power. As a member of one of these groups observed,

> The section on nuclear power in the WGEP [Working Group on Energy Policy of 1977] Report reads like a public relations brochure of the Department of Atomic Energy and does not really examine any of the basic issues. (Shankar, 1985: 85)

The Central Electric Authority's Expert Committee on Fuels for Power Generation opined that "nuclear energy has the potential of providing long-term energy security to the country and all research and development efforts must be pursued to realize this objective" but with the explicit admission that "the cost of generation of nuclear projects have not been calculated" (CEA, 2004: vi).

Regulatory Bodies

Civilian nuclear installations come under the regulatory purview of the Atomic Energy Regulatory Board (AERB). They also have to obtain environmental clearances from the Ministry of Environment and Forests.

Safety Regulation

The DAE established the AERB to oversee and enforce safety in all nuclear operations in 1983. This was modified in 2000 to exclude facilities involved, even peripherally, in the nuclear weapons program. The AERB reports to the Atomic Energy Commission (AEC), whose chairman is always the head of the DAE. The chairman of NPC is also a member of the AEC. Thus, both the DAE and NPC exercise administrative powers over the AERB. Its budget comes from the DAE. There are, therefore, structural limits on the AERB's effectiveness.

This administrative control is compounded by the AERB's lack of technical staff and testing facilities. As A. Gopalakrishnan, a former chairman of the AERB, has observed,

> 95 percent of the members of the AERB's evaluation committees are scientists and engineers on the payrolls of the DAE. This dependency is deliberately exploited by the DAE management to influence, directly and indirectly, the AERB's safety evaluations and decisions. The interference has manifested itself in the AERB toning down the seriousness of safety concerns, agreeing to the postponement of essential repairs to suit the DAE's time schedules, and allowing continued operation of installations when public safety considerations would warrant their immediate shutdown and repair. (Gopalakrishnan, 1999)

Elsewhere, Gopalakrishnan has pointed to an example of direct interference from the AEC, in the context of the 1994 collapse of the containment dome of one of the reactors under construction at Kaiga, Karnataka.

> When, as chairman, I appointed an independent expert committee to investigate the containment collapse at Kaiga, the AEC chairman wanted its withdrawal and matters left to the committee formed by the NPC [managing director]. DAE also complained to [the prime minister] who tried to force me to back off. (Pannerselvan, 1999)

Finally, the AERB's ability to force the DAE to carry out its directives is limited. For example, according to Gopalakrishnan:

> [The] AERB had directed the DAE to carry out an integrated Emergency Core Cooling System (ECCS) testing in Kaiga I and II as well as RAPS III and IV before start up. It also wanted proof and leakage tests conducted on the reactor containment. And finally, a full-scope simulator was to be installed for operator training. None of these directives have been complied with so far. (Pannerselvan, 1999)

Environmental Regulation

The Environmental Impact Assessment (EIA) Notification of 1994 listed "nuclear power and related projects such as heavy water plants, nuclear fuel complex, rare earths" while the EIA Notification 2006 lists "nuclear power projects and processing of nuclear fuel" as requiring environmental clearances. However, not all facilities involved in processing nuclear fuel are subject to this procedure. For example, the nuclear reprocessing plants located at Trombay, Tarapur and Kalpakkam that chemically process radioactive spent fuel discharged from nuclear reactors do not fall under the EIA Notification (BARC, 2008).

The EIA process has not been effective (Ramana and Rao, forthcoming; Rao and Ramana, 2008). All nuclear projects, barring one, have received environmental clearances. In the case of the one project that was rejected, the location had to be shifted because of fears of contamination of drinking water. However, even in that case, the pathway and potential impact of such contamination were not identified in the EIA. The EIA reports that form the basis of the clearance have been mostly shoddy, with technical flaws and crucial oversights. As with government committees concerned with energy policy, expert committees that recommend whether or not a project should be given environmental clearance always include representatives from the DAE and its allied organizations.

In practically all cases, the overwhelming opinion expressed by participants at public hearings for nuclear facilities has been in opposition to the project. These views have been uniformly ignored by decision makers. Local administrative authorities conducting public hearings have clearly sided with project proponents, allowing them to dominate the proceedings, denying members of the public the right to present their views and preparing minutes of the meetings that make it appear as though there was little opposition and that project proponents have assuaged any remaining public concerns.

The US-India Nuclear Deal

As previously mentioned, India is no longer subject to various nuclear trade regulations imposed primarily as a result of the 1974 and 1998 nuclear tests, because the Nuclear Suppliers Group (NSG) has given a special waiver to India. The waiver was the result of a three-year process that began publicly in July 2005, when US President George W. Bush and Indian Prime Minister Manmohan Singh issued a joint statement laying the ground for resuming US and international nuclear aid to India. In March 2006, the Indian government designated several domestically constructed nuclear facilities as civilian, and volunteered them for IAEA inspection in a phased manner. This was followed by the US Henry Hyde Act[7] and a 123 agreement between the two countries.[8]

The deal marked a new phase in the bilateral relationship between United States and India, requiring both countries to reverse historical policies. As described earlier, the US played a key role in putting in place the very nuclear export control norms the NSG waived for India. India has traditionally been opposed to international safeguards at domestically constructed nuclear facilities. In the case of the United States, the main motivations were geo-strategic and commercial (Mian and Ramana, 2006; Ghoshroy, 2006). The DAE's motivations derived from the need for external assistance to increase the scale of the Indian nuclear program and a shortfall of uranium production due to inadequate mining capacity (Mian and Ramana, 2005).[9]

The deal is expected to result in a substantial number of reactor imports by India. The DAE also hopes there may be possibilities for nuclear exports.

Economics

The promise offered by the DAE was not only that nuclear power would form an important component of India's electricity supply, but that it would be cheap. As early as 1958, barely a few years after the DAE was set up, Bhabha projected that "during the next 10 to 15 years…the costs of [nuclear] power [would] compare very favourably with the cost of power from conventional sources in many areas" (Bhabha and Prasad, 1958). The "conventional source" to which the DAE was comparing nuclear energy was coal, India's staple source of electricity. Since the bulk of India's coal deposits are in the eastern part of the country, "many areas" referred to regions remote from coal mines. The higher cost of transporting coal to such areas would make nuclear power more competitive.

During Bhabha's time, and before the first power reactors were constructed, the DAE claimed that for distances greater than about 600 km, nuclear power would be cheaper than coal. Once the first few reactors were constructed, it was apparent that construction costs were substantially greater than projected. By the 1980s the DAE was forced to revise its claims to the cost of nuclear power comparing "quite favourably with coal fired stations located 800 km away from the pithead." Extraordinarily, though, it promised that nuclear power "in the 1990s would be even cheaper than coal fired stations

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[7] The Hyde act grants the US president limited and conditional authority to waive the longstanding American legal restrictions on nuclear trade with countries, such as India, that have tested nuclear weapons, have not joined the NPT and do not allow comprehensive international nuclear safeguards.

[8] The name derives from Section 123 of the United States Atomic Energy Act of 1954, titled "Cooperation With Other Nations," which is a prerequisite for nuclear trade and other forms of cooperation between the United States and any other nation.

[9] This was evident in the statement from an unnamed official to the British Broadcasting Corporation (BBC) soon after the US-India deal was announced: "The truth is we were desperate. We have nuclear fuel to last only till the end of 2006. If this agreement had not come through we might have as well closed down our nuclear reactors and by extension our nuclear programme" (Srivastava, 2005).

at pithead" (Srinivasan, 1985). That projection, too, was not fulfilled. By the late 1990s, all the DAE could claim was that the "cost of nuclear electricity generation in India remains competitive with thermal [electricity] for plants located about 1,200 km away from coal pit head, when full credit is given to long term operating cost especially in respect of fuel prices" (Nema, 1999).

Economics of Pressurized Heavy Water Reactors

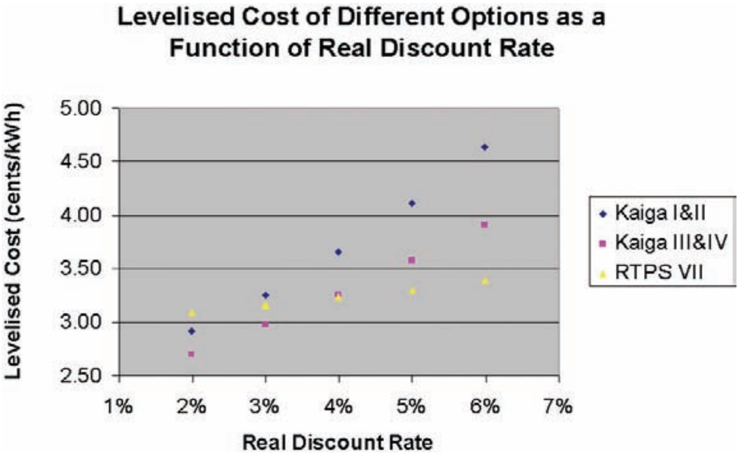
Not even the 1,200 km projection was borne out when tested empirically by comparing the construction and operating costs of actual reactors and coal plants, as opposed to generic cost estimates. Two collaborators from the International Energy Initiative and I used the standard discounted cash-flow methodology[10] to compare the costs of generating electricity at the Kaiga nuclear reactors and the Raichur Thermal Power Station (Ramana, D'Sa and Reddy, 2005). We deliberately assumed that the coal came from mines 1,400 km away.

Because of the different cost structures of the two sources of power, the discount rate, a measure of the value of capital, is a key variable. Nuclear power, a very capital intensive technology, is competitive only for low discount rates (see Figure 1). But given multiple demands on capital for infrastructure projects, including electricity generation, very low discount rates are not realistic.[11] At a real discount rate of five percent, roughly what is recommended by the Central Electricity Regulatory Commission (CERC, 2006), nuclear power from the Kaiga reactors is about eight percent more expensive than thermal power from Raichur (Ramana, 2007).

The Raichur plant is somewhat atypical because of the assumption about where the coal came from – 1,400 kilometers away. In reality, over a third of all of India's coal plants are at the pithead and a further quarter or more are within 500 km of one (Chowdhary, 1998). Thus, except for isolated cases, nuclear power will generally be far more expensive than thermal power.

This economic comparison is largely based on assumptions favourable to nuclear power. For example, the comparison does not include liability insurance against accidents, since the government has not required that of nuclear power plants. There is no equivalent of the US Price Anderson Act, which requires nuclear utilities to cover each reactor they operate by the maximum available amount of insurance; in 2005, the limit was US$300 million per plant, but the government acts as the ultimate insurer if the damage from a catastrophic accident costs more than the amount covered by the insurance package. In India, since nuclear reactors and other facilities are operated by government organizations, the entire burden of an accident is on the government.

Figure 1: Busbar Generation Costs of Kaiga I&II, Kaiga III&IV (projected costs), and RTPS VII at 80 percent Capacity Factor



Source: Ramana, D'Sa and Reddy (2005) and author's calculations

Most important, following the methodology adopted by the DAE (Thakur and Chaurasia, 2005), we have not included the costs of dealing with radioactive waste from nuclear power. In essence, the NPC, which operates the heavy water reactors, simply hands over the irradiated spent fuel from its reactors to the DAE. However, since reprocessing is a service rendered by the DAE to the NPC, the rational choice for the DAE would be to charge a fee for it. If even half the cost of reprocessing is included in the tariff for nuclear power, it would be 25 percent more expensive than thermal power from coal.

By not charging a fee for reprocessing, the DAE, in effect the taxpayer, is offering the NPC a subsidy.[12] The DAE seems to do this because the recovered plutonium is used to fuel breeder reactors that produce more plutonium than they consume. However, the economic competitiveness of breeder reactors is suspect.

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[10] In this approach, all costs are discounted to some arbitrary but fixed reference date; the total cost reckoned at this reference point is the sum of the present values (PV) or future values (FV) of costs discounted to this date. For a description of this methodology, see (Brealey and Myers, 2000).

[11] Typical values chosen in costing electricity generation (or saving) technologies in India have ranged from 8 to 10 percent (real values). For examples, see (Shukla, Ghosh and Garg, 2003) and (Nouni, Mullick and Kandpal, 2006).

[12] The DAE also subsidizes the Nuclear Power Corporation by providing heavy water at a low lease rate, and at a price much lower than the cost of production (Muralidharan, 1988; Ramana, 2007).

Economics of Breeder Reactors

The DAE has been pursuing its breeder program without ever examining the economics of producing electricity using such reactors. The argument offered for this pursuit is that that India has only "modest uranium reserves" of about 60,000 tonnes (Kakodkar, 2006). While widely articulated, this formulation is misleading. India's uranium resource base cannot be represented by a single number. For example, the Nuclear Energy Agency's *2007 Red Book* states that the known conventional resources amount to 91,100 tonnes of uranium, with 61,100 tonnes in the Reasonably Assured Resources (RAR) and 30,000 tonnes in the Inferred Resources (IR) categories (NEA, 2008: 207).[13] It also reported an additional 67,900 tonnes in unconventional resource categories in which less confidence can be placed and which are likely more difficult to mine.

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, the uranium resources can only be specified as a function of price. In other words, if the PHWR operator is willing to bear a higher cost for fueling the reactor, the amount of uranium available will be much larger. To address the argument about India's limited uranium reserves, an economist and I compared the cost of generating electricity at the PFBR, India's first commercial scale breeder reactor, with a PHWR, the mainstay technology of the country's nuclear program. We did so as a function of uranium price and calculated the crossover price when the two technologies generate electricity at the same cost (Ramana and Suchitra, 2009; Suchitra and Ramana, forthcoming).

We considered the same set of cost components for both the PFBR and the PHWR, namely construction of the reactor (capital cost), fueling, operations and maintenance, decommissioning, refurbishment, working capital, and management of low-level radioactive wastes.[14] For the PHWR, the fueling cost includes the cost of uranium and the cost of fuel fabrication. Also included are the costs of the initial heavy water inventory and of replacing the heavy water lost during routine operations. For the PFBR, the fueling cost includes that of producing plutonium through reprocessing and fabricating it into MOX fuel.

The plutonium for the initial core as well as for the first few reloads has to come from reprocessing PHWR spent fuel. The DAE has never published what it costs to reprocess spent fuel at its facilities. We therefore used government budget documents to calculate the construction and operating costs of the Kalpakkam Atomic Reprocessing Plant (KARP) and associated facilities, and used these to compute the cost of reprocessing (Ramana and Suchitra, 2007).[15] At a real discount rate of six percent, our estimate of the total cost of reprocessing is US$659/kg of spent fuel. This rate is dependent on the efficiency of the plant, for which we assume the optimistic value of 80 percent.[16] Assuming losses of one percent of the plutonium in the spent fuel, this translates to a plutonium cost of US$178/g.

The PFBR design requires an initial inventory of 1.9 tons of plutonium in its core and thus just the cost of loading the reactor with plutonium will add substantially to the capital costs of the reactor. Subsequently the plutonium for the PFBR is obtained from reprocessing its own spent fuel. Because of the higher plutonium content of the PFBR spent fuel, the cost of such plutonium would be lower; we estimate it to be US$43/g (Ramana and Suchitra, 2009; Suchitra and Ramana, forthcoming).

Because of the high cost of plutonium, a result of the expensive reprocessing plants required to extract the material from spent fuel, the main cost components of generating electricity at the PFBR turn out to be those

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[13] Globally, the annual Red Books produced by the IAEA and NEA are the standard sources of information on uranium resources. These have been published since the mid-1960s and are based on information provided by various countries to the IAEA. The Red Book categorizes uranium resources into conventional or unconventional resources (NEA, 2002: 13-15). "Conventional resources are those that have an established history of production, where uranium is a primary product, co-product, or an important by-product (e.g. from the mining of copper and gold). Very low grade resources or those from which uranium is only recoverable as a minor by-product are considered unconventional resources." All other sources of uranium are considered unconventional resources. The Red Books further divide conventional resources into multiple categories based on how confident one can be of the resource estimates. The most important of these are Reasonably Assured Resources (RAR) and Inferred Resources (IR), previously known as Estimated Additional Resources (EAR). RAR refers to uranium resources that have a high assurance of existence because they occur in known mineral deposits. Because their grade is known, it is usually possible to estimate the quantities that may be recovered from that deposit within specific production cost ranges using currently proven mining and processing technology. IR refers to uranium deposits that are not included in the RAR category, and are inferred to exist on the basis of direct geological evidence. For these, though, there is usually inadequate knowledge about the deposits' characteristics to categorize the resource as RAR. Estimates in this category are less reliable than those for RAR. There are also other unconventional resources, such as phosphate deposits, that are not included in the Red Books.

[14] In line with the DAE's philosophy of not treating spent fuel as waste, we do not include the cost of dealing with this highly radioactive material; however, in the case of the PFBR, the cost of reprocessing its spent fuel is indirectly included in the fueling cost.

[15] KARP is chosen as a reference facility because it is the most recently constructed plant and is to serve as a standard design for future plants (Dey, 2003).

[16] The relatively scant amounts of publicly available data suggest that past performance of reprocessing plants in India have been mediocre. PREFRE, at Tarapur, operated at an average capacity factor of less than 25 percent for over a decade (Hibbs, 1995).

related to plutonium. The higher fueling cost offsets the projected difference between the cost of constructing the PFBR and PHWRs. BHAVINI has estimated the total construction cost of the PFBR at US$638 million (in 2004 dollars), or US$1,276/kW. This is about US$95/kW less than the projected costs of the PHWRs under construction, but more than the projected costs of the 700 MW PHWRs the DAE plans to build in order to take advantage of economies of scale.

The PFBR cost estimate could be compared to estimates of breeder reactor construction costs elsewhere. Construction costs for the French Phenix reactor totaled FF800 million (at 1974 values) or US$800 million at 2004 values (US$3,200/ kW) (IPFM, forthcoming). However, a further €600 million (US$870 million at 2004 values) was spent on Phenix upgrades between 1997 and 2003. The 1,240 MW Superphenix was far more expensive, with an initial investment of FF28 billion (at 1985 values, or US$4.9 billion at 2004 values) (NUKEM, 1997: 15). The 300 MW Kalkar reactor in Germany cost DM7 billion (1985 values or US$3.6 billion at 2004 values) (Neffe, 1985).

Technically, breeder reactors can be expected to be more expensive for two reasons. First, the use of molten sodium as coolant has several operational requirements, such as heating systems to keep the sodium molten at all times, and safety requirements, such as extensive firefighting equipment (Farmer, 1984). The second reason stems from the realization that accidents at breeder reactors could lead to the release of large quantities of explosive energies (Bethe and Tate, 1956). They therefore need even more extensive safety features, which are a significant component of the total capital cost.

Despite these many reasons to expect cost escalation for the PFBR, we used the DAE's estimate. Even with this low estimate, and for an optimistic load factor of 80 percent, at a real discount rate of six percent and at a uranium price of US$200/kg, electricity from the PFBR will be approximately 40 percent more expensive than from PHWRs. If the PFBR was compared with future 700 MW PHWRs, which should have lower construction costs (Bhardwaj, 2006; Thakur and Chaurasia, 2005), electricity from the PFBR will be about 80 percent more expensive. 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" (Chetal et al., 2006). Our results show that the PFBR will not be viable, even with favourable assumptions. If these assumptions do not hold, then its economic viability will be further reduced.

One assumption that is particularly dubious is that the PFBR will operate at a load factor of 80 percent. As the table below shows, breeder reactors across the world have operated with relatively low load factors. If the PFBR experience were to be similar, a load factor of 50 percent might be more plausible, and this would result in PFBR electricity being 87 percent to 139 percent more expensive than PHWRs.

Figure 2: Performance of Breeder Reactors

	Phenix, France	**Prototype Fast Reactor, UK**	**BN-600, Russia**	**Superphenix, France**
Date of Grid Connection:	December 13, 1973	January 10, 1975	April 8, 1980	January 14, 1986
Cumulative Load factor (%)	41.34	23.87	73.48	6.6

Source: International Atomic Energy Agency (2009).

As mentioned earlier, the main rationale offered for pursuing expensive breeders is the shortage of uranium. We examined this by increasing the price of uranium from US$200/kg to the "crossover value" where breeders become competitive. For the optimistic base case, with a PFBR load factor of 80 percent and a construction cost lower than that of the PHWR, the levelized costs of electricity from the PFBR and PHWR are equal at a uranium price of US$890/kg. If the PFBR was compared to future PHWRs that are expected to be cheaper, the crossover value is US$1,375/kg.

These prices are much higher than current values. The distribution of uranium among the major geological reservoirs in the earth's crust corresponds to a roughly 300 fold increase in the estimated amount of recoverable uranium for every ten fold decrease in ore grade (Deffeyes and MacGregor, 1980). If higher costs for uranium are accepted, going from US$200/kg to US$890/kg, the crossover uranium price if the assumptions made were favourable to the PFBR, might increase the available uranium reserves by a factor of about 40. This is an underestimate because it ignores the general trends of reduced mining costs due to learning and improved technology (Schneider and Sailor, 2005). Less favorable assumptions would result in greater quantities of uranium that are economically recoverable. In any case, India should have sufficient uranium to fuel PHWRs for decades, without reprocessing and breeder reactors. India has already embarked on efforts to recover uranium from unconventional resources such as monazite, thorium hydroxide and phosphoric rock (Singh, 1999; Mukherjee and Singh, 2003).

Safety

Of all electricity generating technologies, nuclear power alone comes with the possibility of catastrophic accidents. This was most dramatically illustrated by the Chernobyl accident of 1986, but there have been other accidents that have resulted in damage to public health and the environment. While the DAE, like other organizations involved in nuclear activities, often verbalizes safety goals (for example, "safety is our number one priority"), performance and decision making often depart from public pronouncements. As a way of assessing the potential for accidents at Indian nuclear facilities, three related questions must be answered. What have been the experiences with accidents, both small and large, at DAE's facilities? What practices lie beneath the DAE's planning and operations? What has been the DAE's attitude towards nuclear safety?

Accidents

In its submission to the IAEA as part of its responsibilities under the 1994 Convention on Nuclear Safety, the DAE stated that:

> Safety is accorded overriding priority in all activities. All nuclear facilities are sited, designed, constructed, commissioned and operated in accordance with strict quality and safety standards… As a result, India's safety record has been excellent in over 260 reactor years of operation of power reactors and various other applications. (GoI, 2007)

The actual historical record, however, has not been as excellent as this statement projects. Practically all nuclear reactors and other facilities associated with the nuclear fuel cycle operated by the DAE have had accidents of varying severity. The description of some accidents offers a sense of the lack of importance given to nuclear safety by the DAE. This history suggests the organization cannot be trusted to safely manage hazardous technologies (Kumar and Ramana, forthcoming).

Narora 1993

The most serious accident at an Indian nuclear reactor occurred on March 31, 1993. Early that morning, two blades of the turbine at the first unit of the Narora power station (two 220 MW PHWRs) broke off due to fatigue. These sliced through other blades, destabilizing the turbine and making it vibrate excessively. The vibrations caused pipes carrying hydrogen gas that cooled the turbine to break, releasing the hydrogen which soon caught fire. Around the same time, lubricant oil also leaked. The fire spread to the oil and through the entire turbine building. Among the systems affected by the fire were four sets of cables that carried electricity, which led to a general blackout in the plant. One set supplied power to the secondary cooling systems, which were consequently rendered inoperable. In addition, the control room became filled with smoke and the staff were forced to leave it about 10 minutes after the blade failure.

The operators responded by manually actuating the primary shutdown system of the reactor 39 seconds into the accident (Koley et al., 2006). Although the reactor was shut down, some operators, concerned about re-criticality, climbed onto the top of the building and, under battery-operated portable lighting, manually opened valves to release liquid boron into the core to slow down the reaction. It was necessary to do so because even though it was shut down, the reactor continued to generate heat; the fuel rods in a reactor accumulate fission products — the elements created when a uranium atom splits — and these continue to undergo radioactive decay and produce heat. While this so-called decay heat is only a small fraction of the power produced when the reactor is operating, it is generated even when the reactor is shut off. If not removed promptly, decay heat can cause the fuel to reheat and melt down. Thus, the reactor must continue to be cooled even after shutdown. To accomplish this task, operators had to start up diesel fire pumps to circulate water meant for fire control (NEI, 1993).

It took 17 hours from the time the fire started for power to be restored to the reactor and its safety systems. Operators who were forced to leave the control room because of smoke could not re-enter for close to 13 hours. An attempt was made to take control of the plant from the emergency control room; but, since there was no power available, the Unit 1 control panel of the emergency control room was unusable. Thus, Narora was almost unique in that the operators had no indication of the condition of the reactor and were, in effect, "flying blind" (Nowlen, Kazarians and Wyant, 2001).

The Narora accident has been the DAE's closest approach to a catastrophic accident. More worrisome is the evidence that the accident could have been foreseen and prevented.

First, the failure of the turbine blades was avoidable. In 1989, General Electric Company communicated information to the turbine manufacturer, Bharat Heavy Electricals Limited (BHEL), about a design flaw which led to cracks in similar turbines around the world. They recommended design modifications, and the manufacturer responded by preparing detailed drawings for NPC, which operated the Narora reactor. In addition to General Electric, the manufacturer of the turbine, BHEL, also recommended that NPC replace the blade design before an accident occurred. However, NPC did not take any action until months after the accident (Gopalakrishnan, 1999).

Second, even if the turbine blade failed despite modification, the accident might have been averted if the safety systems had been operating, which they presumably would have if only their power supply had been encased in separate and fire resistant ducts. By the time the Narora reactor was commissioned, this was established wisdom in the nuclear design community and had been ever since the fire at Browns Ferry in the US in 1975. That accident resulted in a mandate to make significant changes at all US nuclear plants (Ramsey and Modarres, 1998: 106). The physical and electrical systems were altered, with built-in redundancies, to prevent fires. Other countries adopted similar measures. All of this took place well before the Narora plant attained criticality in 1989. Nevertheless, the plant was constructed with backup power supply systems laid in the same duct, with no fire-resistant material enclosing or separating the cable systems.

Third, the DAE had not taken any serious steps towards fire mitigation despite earlier fire accidents at its own reactors. In 1985, an overheated cable joint at RAPS II caused a fire that spread through the cable trays and disabled four pumps (IAEA, 1986: 244; Gopalakrishnan, 1999). A few years later, in 1991, there were fires in the boiler room of the same unit and the turbo generator oil system of RAPS I (IAEA, 1992: 394-396).

The factors that contributed to the Narora accident were repeatedly present prior to the accident. In particular, excessive vibrations in the turbine bearings were common in Indian reactors. In 1981, RAPS II was shut down twice because oil leakage in the turbine building led to high levels of sparking in the generator exciter (IAEA, 1982: 235). After it was restarted, it had to be shutdown yet again when it was found that large amounts of oil had leaked from the turbine governing system. Only when the reactor was restarted a third time, in early 1982, were the high vibrations of the turbine bearings noticed and the failure of turbine blades discovered (IAEA, 1983: 250). This led to a prolonged shutdown of more than 5 months; even after this problem had apparently been fixed the reactor had to be shut down once again because of high turbine bearing temperatures (IAEA, 1983: 230). Again in 1983, high vibrations were noticed in turbine generator bearings and it was revealed that two blades in the second stage of the high pressure rotor had sheared off at the root (IAEA, 1984: 292). In 1985, the first unit of the Madras Atomic Power Station (MAPS I) was shutdown repeatedly because of high bearing vibrations in the turbine generator (IAEA, 1986: 240). RAPS I had to be shutdown due to high bearing vibrations in 1985, 1989, and 1990 (IAEA, 1986: 242; 1990: 302; 1991: 298).

Oil leaks have also been common in Indian reactors. In 1988, MAPS II was shut down due to an oil leak from the generator transformer (IAEA, 1990: 288). In 1989, a large spark was observed from slip rings on the exciter end of the turbine in MAPS I; there were also two other fires in the same reactor near the primary heat transport system (IAEA, 1990: 298). Oil leaked from a turbine bearing in MAPS II in 1989 (IAEA, 1990: 300). In 1992, there was an oil leak in the turbine stop valve in MAPS II (IAEA, 1993: 288). In addition in 1992, there were two separate oil leak incidents in the Narora I turbine generator system (IAEA, 1993: 289). There was at least one hydrogen gas leak prior to the Narora accident: this happened in 1991 in the generator stator water system of MAPS II (IAEA, 1992: 390).

The DAE simply did not take these experiences into account while designing the Narora reactor. Fortunately, the uproar from the Narora accident was great enough that the DAE appears to have incorporated some design changes. The head of the AERB at that time, Gopalakrishnan, appears to have played an important part in ensuring improvements. While these changes might prevent an identical accident, they do not necessarily rule out other kinds of accidents. Changes made to complex technologies might have unanticipated consequences and produce new accident pathways (Perrow, 1984).

Kalpakkam 2003

On January 21, 2003, some employees at the Kalpakkam Atomic Reprocessing Plant (KARP) were tasked with collecting a sample of low-level waste from a part of the facility called the Waste Tank Farm (WTF). Unknown to them, a valve had failed, resulting in the release of high-level waste, with much greater levels of radioactivity, into the part of the WTF where they were working. Although the plant was five years old, no radiation monitors or mechanisms to detect valve failure had been installed in that area. The accident was recognized only after a sample was processed. In the meantime, six workers had been exposed to high doses of radiation (Anand, 2003).

Apart from the lack of monitoring mechanisms, the greatest cause for concern was the response of management, in this case BARC. Despite a safety committee's recommendation that the plant be shut down, BARC's upper management decided to continue operating the plant. The BARC

Facilities Employees Association (BFEA) wrote to the director setting forth ten safety related demands, including the appointment of a full time safety officer. The letter also recounted two previous incidents where workers were exposed to high levels of radiation in the past two years, and how officials had always cited the existence of an emergency situation as a reason for the Health Physics Department's failure to follow safety procedures. Once again there was no response from management. In desperation, some months later the union resorted to a strike. The management's response was to transfer some of the key workers involved in the agitation and give notice to others; two days later, all striking workers returned to work. The BARC director's public interpretation was essentially that if the place had not been safe, the workers would not have returned. Finally, the union leaked information about the radiation exposure to the press.

Once the news became public, management grudgingly admitted this was the"worst accident in radiation exposure in the history of nuclear India" (Anand, 2003). But it claimed the "incident" resulted from "over enthusiasm and error of judgment" on the part of the workers (Venkatesh, 2003). Management also tried to blame the workers for not wearing their thermoluminescent dosimeter badges, but this has nothing to do with the accident; badges would not have warned the workers about radiation levels until well after they were exposed.[17]

For its part, the BFEA claimed the accident was only to be expected, and that because of the unrelenting pace of work at KARP and "unsafe practices being forced on the workers," accidents have become regular (Anonymous, 2003). Thus, there is no consensus among management and workers on how to run the Kalpakkam plant safely. Instead, operations were marred by discontent and opacity, and management repeatedly disregarded workers' attempts to have safety features installed.

Practices

One can look at safety even in the absence of major accidents, in the way that day-to-day work is carried out at DAE facilities.

Patterns

One indicator of poor safety practices is repeated occurrences of similar accidents. An important example is the set of problems that led to the Narora accident, which have persisted in many reactors. Other examples are regular leaks and heavy water spills. While these leaks are not themselves serious safety hazards, they could be the precursors to more serious accidents.[18]

Such leaks started with RAPS, the first heavy water reactor constructed in India (Ghosh, 1996). Despite much effort – understandable because heavy water is expensive and hard to produce – the DAE has not managed to contain the leaks. In 1997 alone, such leaks occurred at the Kakrapar I, MAPS II and Narora II reactors (IAEA, 1998: 301-320). The leaks could be significant. For example, on April 15, 2000, there was a leak of seven tons of heavy water at the Narora II reactor (AERB, 2001: 13). Three years later, on April 25, 2003, there was a six ton leak at the same reactor (AERB, 2004).

The 2003 leak occurred while a device called BARCCIS (Bhabha Atomic Research Centre Channel Inspection System), which is used to inspect coolant tubes in reactors, was in operation. After a similar leak in March 1999 at MAPS, the Atomic Energy Regulatory Board reviewed the BARCCIS system and suggested design changes, operating procedures and training (AERB, 2004: 18). A similar leak at the Narora reactor despite these changes suggests technical weaknesses in the regulatory board, fundamental flaws in the system or continued operator errors.

Inoperative Safety Systems

A second notable and disturbing trend is the frequent failure of safety devices. These are the mechanisms by which control of the reactor ought to be maintained under unanticipated circumstances. If they do not work as expected, it is more likely that a small event could cascade into a major accident. An related problem is that of safety devices left in an inoperative state or neglect of periodic maintenance.

An example of how minor failures contributed to escalating an accident was the 1993 Narora accident discussed earlier. The accident may have been prevented had the smoke sensors in the power control room at Narora detected the fire immediately. Since that did not happen, the fire was detected only when the flames were noticed by plant personnel (Srinivas, 1993). A different complication arose three hours and fifty minutes into the accident when the two operating diesel-driven fire water pumps tripped

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[17] These badges measure cumulative exposure over a period of time, and are meant to be submitted to the health physics department for assessment.

[18] Further, irradiated heavy water has some admixture of tritium; exposure to heavy water can also lead to high radiation exposure (Ramana, 1999).

inexplicably (Nowlen, Kazarians and Wyant, 2001). As yet, the cause for the failure has not been identified. A third pump was out of service for maintenance.

Many of these problems are recurring. In 2005, for example, the AERB found instances of failure in fire detectors at Kakrapar and in the power supply for emergency cooling at the Madras Atomic Power Station (PTI, 2005). Heat transport pumps are also frequently unavailable for many reasons, most commonly because of frequency fluctuations in the electricity grid. In 2004, MAPS-2 was shut down for eight days because the two main primary coolant pumps were unavailable. After it was restarted, the reactor had to be shut down again because the motor bearings of one of the pumps had to be replaced.

Choices in Design and Plans

The DAE has often made choices in which different safety considerations have been traded off against each other. The best example is the prototype fast breeder reactor (PFBR) under construction. The DAE's choice of containment design and various reactor parameters for the PFBR are directly linked to cost reduction efforts made in the 1990s (Bhoje, 2001). The DAE has also emphasized that "minimizing 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). This has significant safety implications (Kumar and Ramana, 2008).

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 a "Core Disruptive Accident" (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, reactivity could increase, leading to further core rearrangement and a potential feedback loop. Another feedback effect in the PFBR design is a relatively large positive sodium void coefficient. If the coolant heats up and becomes less dense, forms bubbles, or is expelled from the core, reactivity increases. The magnitude of the void coefficient is a measure of the feedback and tends to increase with core size.[19]

Compounding the safety risks that come with this large and positive sodium void coefficient, the PFBR design also has a relatively weak containment building, designed to withstand only 25 kilopascals (kPa) of overpressure (Chetal et al., 2006). The containment building is meant to act as the final barrier that stands in the way of radioactive materials escaping into the atmosphere during a catastrophic accident. The maximum overpressure the PFBR is designed to withstand is low compared to most other demonstration reactors.

It is possible to design containment buildings to withstand much higher pressures. Containment buildings for light water reactors are routinely designed to withstand more than 200 kPa (APS Study Group, 1985: S94). The design for the DAE's planned 700 MW pressurized heavy water reactors includes containment buildings designed to withstand up to 156 kPa (Bhardwaj, 2006). The DAE justifies this choice of containment design by arguing that its safety studies demonstrate the maximum overpressures expected in a CDA are below the building's limits. But these are based on favourable assumptions, in particular, that only limited parts of the reactor core are involved in the CDA and that only about one percent of the thermal energy released is converted into mechanical energy. These cannot be considered "reasonable worst case" assumptions. Nevertheless, based on such assumptions, the DAE estimates the maximum credible energy release in a CDA is 100 MJ (megajoules) (Chetal et al., 2006). The DAE then calculates that such a CDA leading to sodium leakage into the containment will result in a containment overpressure of 20 kPa.

Figure 3: 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

Source: Calculations based on Waltar and Reynolds (1981: 524)

There are, however, good reasons to consider much larger energy releases, to the extent of several hundred MJ, in the evaluation of the safety of reactor designs, especially one as large as the PFBR. CDA energy releases calculated for breeder reactors in other countries can prove useful comparators. Figure 3 lists the maximum energy released during a CDA and the ratio of energy released to the

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[19] 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.

power of the reactor. The ratio is useful to consider because larger reactors, which generate more power, typically have larger cores with greater quantities of radioactive materials in them. Both as absolute figures and when scaled by reactor power, these estimates for other breeder reactors are much higher than the DAE's estimate for the PFBR.

As an alternative to the DAE's estimate, an engineer and I calculated that if a larger fraction of the reactor core is involved in a CDA, the energy release from a CDA could be as high as 650 MJ, which could lead to an overpressure of about 40 kPa on the containment, clearly much higher than the design limit of the containment building (Kumar and Ramana, 2008). In arriving at this estimate, we followed the DAE in assuming an efficiency of conversion of thermal into mechanical energy of one percent. However, there is some evidence that the conversion efficiency could be higher, about four percent (Berthoud, 2000: 594). Higher conversion factors would imply higher mechanical energy releases and thus more significant overpressures and a greater possibility of containment failure.

To summarize, safety considerations have not been adequately incorporated into the design of the PFBR and design choices have been rationalized through studies that use assumptions not justified by empirical studies. This problem is compounded by an absence of peer review mechanisms and an unwillingness to expose technical studies to outside criticism.

A similar set of choices were also made for emergency plans. These do not adequately reflect the gravity of a potential nuclear accident and the need for rapid action to protect the public. Though the DAE has argued that nuclear accidents are impossible in India, it has also prepared emergency plans for dealing with such accidents. Such plans are typically justified as "a measure of abundant caution" by DAE personnel (Sundararajan, 1991), but the DAE has made them inaccessible to the public. As a result, knowledge of what to do in the event of an accident among the inhabitants of areas surrounding nuclear facilities is minimal. Among those living near the Kalpakkam nuclear complex, 68.8 percent of those surveyed were completely ignorant of what to do in the event of a nuclear accident (MAI, 1993).

An emergency plan for the Kakrapar power station in the state of Gujarat, which was unintentionally released, would clearly not work in the event of an actual accident (Rawat, 1998). The two 220 MW reactors are located on the banks of a river, which only had one bridge across it in the vicinity of the power station. The plan required all those evacuated to travel across this single bridge, a recipe for a major traffic bottleneck. The plan also absurdly required people in villages and towns further upstream to move towards the reactor first, cross the bridge and then travel away. Finally, several facilities, such as schools, assigned as temporary shelters, were grossly inadequate for the likely number of people to be housed there.

Perhaps the best illustration of how unworkable these plans are can be found in accounts of emergency drills occasionally carried out near nuclear reactors. At such drills, officials and local inhabitants are supposed to behave as though a real emergency is underway, but that has not been the case. During an emergency drill near the Tarapur reactors in 1988, the local administration official was informed of the "disaster" at 8:15 PM. According to the emergency plan, the official is supposed to immediately proceed to the Emergency Control Room. Instead, he reached it at 10:50 AM the next morning and it "seemed" to observers that he was "going about the whole thing as if he was attending just another function where he was asked to perform the role of the chief guest" (Shenoy, 1988). At a similar emergency drill around the Kalpakkam site in July 2001, the wireless set of the official in charge of the reactor did not function and "produced just a kee-kee sound" in the words of a staffer (Radhakrishnan, 2001).

Discourse

Despite this historical record of small accidents and near misses, the DAE and its attendant organizations are completely confident the facilities they build and operate are safe. In fact, the former chairman of NPC stated that it is "important" that "the people [operating the nuclear plant] should be confident about safety" (Subramanian, 2000). This confident view should apparently not be just a public position, meant to assuage the concerns of the citizenry and policy makers, but should be deeply internalized.

DAE officials routinely exhort employees to be confident of the safety of their operations. An example of this occurred in the aftermath of the 1999 Tokaimura criticality accident in Japan, when former AERB chairman Gopalakrishnan, warned that "the degree of automation and cross-checks on safety in our older plants are very minimal and one cannot assert at all that an accident like the one which occurred in Japan will not happen in India" (Tribune, 1999). Delivering the Founder's Day Speech, an annual high profile special event held each year at BARC, the head of the AEC's response to Gopalakrishnan's assessment was to suggest that:

> such a statement, made without any scientific basis, was a symptom of the technological diffidence in some persons who considered that as a nation, India was not capable of dealing with high technology… I do not think so. And there is no doubt that all of you, who have a spectacular record of achievements, do not think so. (Anonymous, 1999)

Occasionally, though, some DAE staff have commented on the nature of the challenge involved. One of them observed that unlike developed countries, where industrial and safety culture "developed over a long period has pervaded the national culture," there is still widespread disregard for safety in India (Ray, 1994-95). In contrast, former AEC Chairman Raja Ramanna reportedly said:

> I would like to ask, are we not spending too much money on health and safety? Should we not have a look and find out whether the international standards of safety are indeed that necessary?… Should we follow the international standards blindly? I think we should have courage to look at these standards especially where they are leading to runaway costs. (Ramanna, 1973, cited in Sharma, 1983: 110)

Fortunately, these views have not led to a repudiation of international standards and, at least on paper, the DAE follows these norms. However, due to a lack of transparency, it is not clear how carefully these standards are practiced during operations (Ramana, 2009). In recent years, India has tried to establish itself as a responsible nuclear country and has therefore been even more desirous of a reputation for adhering to international norms.

While the DAE argued on the one hand that these safety concerns have been taken into account in the PFBR design, it also claims such concerns were completely misplaced in the first place. Thus, a DAE official argued that 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 down to 1e-8 per demand, why invest more funds for safety features. (Paranjpe, 1992)

Since they start with the conviction that the reactor is inherently safe and immune from major accidents, DAE analysts do not carry out reliable safety studies, often making unwarranted assumptions, as illustrated by their studies of potential accidents at the PFBR.

DAE officials often point out that safety is not the sole criterion, perhaps not even the overriding one, by which reactor performance should be judged.

> A good reputation can be earned by ensuring a good safety record, but a continuous production is also a must. Winning safety shields is creditable but we all must ensure to achieve excellence in production also. (Bhatia, 1994-95)

Confidence in safety permeates even the DAE's characterization of its understanding of the world around it. The DAE's Reactor Safety Analysis Group declared in 1986:

> For coastal sites, flooding may be due to tropical cyclones, tsunamis, seiches and wind waves. In India, tsunamis and seiches do not occur. Hence cyclones alone have been singled out for detailed study.

This assertion was proven false by the December 2004 tsunami that devastated parts of India. Though that event triggered some additional safety initiatives at coastal reactors, it does not seem to have resulted in introspection within the DAE about how other assumptions underlying their analyses might prove wrong. There is a parallel between the way the DAE concluded that just because no tsunamis and seiches had hit India by 1986 that they "do not occur," and the way it concludes from the record of no catastrophic accidents that its nuclear facilities are safe. The latter simply does not follow from the former.

Such confidence is not conducive to safety. One of the many paradoxes about safety is that "if an organization is convinced that it has achieved a safe culture, it almost certainly has not" (Reason, 2000).

Despite the claims of the Indian nuclear establishment that its facilities are operated safely, the historical record of accidents and the attitudes of upper level and lower level personnel towards safety both suggest that safety is a low priority. The absence of catastrophic accidents at DAE facilities is not evidence of safety. The absence of evidence of "accidents should never be taken as evidence of the absence of risk"…and "…just because an operation has not failed catastrophically in the past does not mean it is immune to such failure in the future" (Wolf, 2001). Or as James Reason argues, "even the most vulnerable systems can evade disaster, at least for a time. Chance does not take sides. It afflicts the deserving and preserves the unworthy" (Reason, 2000).

None of this means a major accident will necessarily occur soon. Due to the multiple factors involved, many of which cannot be quantitatively predicted, the probability of such an accident is difficult to estimate with any reliability. But there is a high likelihood of one occurring eventually, especially if the problems with poor reliability of operations continue. When such an accident occurs, post facto analyses are likely to come to the conclusion, just as with Bhopal or Chernobyl, that it was an accident waiting to happen.

Waste Management

One major concern about nuclear power has been the production of radioactive waste; this concern has been an important factor in the decision by some European countries to phase out nuclear power. Even in those that continue to pursue nuclear power, dealing with spent fuel has been a problem. For the DAE, however, spent fuel is not waste to manage but "a resource to extract plutonium from" and consequently it has pursued reprocessing as the way of dealing with spent fuel (Chidambaram, 1996).[20] The DAE has not revisited this practice, despite several studies based on the experiences of Western Europe countries and the US which found that reprocessing is uneconomical (Bunn et al., 2005; Deutch et al., 2003; Charpin, Dessus, and Pellat, 2000).

Reprocessing

India has three full-scale reprocessing plants. The first, commissioned at Trombay in January 1965, is used to deal with spent fuel from India's two plutonium production reactors. The plutonium produced at this facility is used for nuclear weapons.

The second reprocessing plant, at Tarapur, was commissioned in April 1977, but the first batch of spent fuel rods was fed into it only in April 1978 (Mirchandani and Namboodiri, 1981: 73). After years of trial runs involving spent fuel from plutonium production reactors, the plant started reprocessing spent fuel from safeguarded PHWRs in 1982 (DAE, 1983: 31). It was only in 1987 that reprocessing spent fuel from non-safeguarded PHWRs started (DAE, 1987: 42). In the 1990s, it was reportedly running "substantially" below its nominal capacity, perhaps as low as 25 percent (Hibbs, 1992, 1995).

The third reprocessing facility, the Kalpakkam Atomic Reprocessing Plant (KARP), with a capacity of 100 tHM/y, was commissioned in 1998 (DAE, 2000: 25). This plant was set up primarily to reprocess spent fuel from MAPS (Hibbs, 1997). KARP is to serve as a standard design for future plants (Dey, 2003). After being commissioned in 1998, it has reportedly been operating satisfactorily since 1999 (DAE, 2000, 2001, 2002).

Reprocessing results in large quantities of waste, because radioactive substances are separated from spent fuel into multiple waste streams. The DAE classifies its wastes into Low Level Waste (LLW), Intermediate Level Wastes (ILW) and High Level Wastes (HLW) (DAE, 1990). The term Medium Level Wastes has also been used, presumably, as a synonym for ILW. LLW is in some cases released into the biosphere and is therefore a conduit for various fission products to potentially reach human beings.[21]

Because it contains the bulk of the radioactivity in spent fuel, the greatest concern is HLW. The DAE deals with this waste by immobilizing or vitrifying it – the waste is mixed with glass at a high temperature and allowed to cool, which slows down the diffusion of radionuclides from HLW.[22] These blocks are stored at the Solid Storage & Surveillance Facility (S3F), which uses natural convection air cooling (DAE, 1990). Intermediate level liquid wastes generated in reprocessing plants are concentrated and fixed in cement (DAE, 1992: 2.26).

Gaseous wastes produced during routine operations at nuclear reactors and reprocessing plants are released through stacks (75-100 metres tall) into the environment after filtration. Likewise low level liquid wastes – consisting mostly of tritium but also small quantities of Cesium-137 and Strontium-90 – are released into nearby water bodies, such as the sea in the case of coastal reactors. Data on such releases are scarce – and often conflicting – but suggest that releases at Indian reactors are much higher compared to similar reactors elsewhere.

Geological Disposal

The DAE proposes to dispose of vitrified HLW in geological repositories about 500–600 metres below the ground in some appropriate host rock such as granite or basalt

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[20] Spent fuel from reactors under safeguards is stored at Away-From-Reactor storage facilities and is no longer reprocessed, as it was for a few years when the original reprocessing plant to deal with power reactor spent fuel was first constructed.

[21] Some low level wastes are immobilized in polymer matrices (Sunder Rajan, 1986).

[22] The vitrification is in a borosilicate (SiO_2-B_2O_3-Na_2O_3-TiO_2-MnO_2) matrix system and the vitrified waste product consists of SiO_2 (34.1), B_2O_3 (6.4), Na_2O_3 (13.7), TiO_2 (6.3), MnO_2 (9.3), and waste oxides (30.2 Wt%) (Raj et al., 1995).

(Raj, Prasad and Bansal, 2006). Some alpha wastes are also slated to be disposed of in similar fashion (Sunder Rajan, 1986). Initially, deep geological formations in the southern Indian peninsula were explored as likely burial sites. A number of bore holes 0.6 miles deep were dug in an abandoned chamber of the Kolar gold mines to test the formation's behaviour under simulated radioactive decay heat (Chellaney, 1987). Those tests evidently did not yield the desired results and in 1999 it was reported that an area of about 100 square kilometres in the state of Rajasthan in the western part of the country had been identified as suitable for burying wastes. This led to public protests from local communities. Shortly afterwards, the government announced in parliament that it had not taken any decisions on the disposal of nuclear waste, and such a decision might "take another two decades of research and development" (PTI, 2000). So far no geological disposal site seems to have been finalized.

Public Perception

In contrast to the enthusiasm for nuclear power that successive governments have displayed, plans for every new nuclear reactor and uranium mine since the early 1980s have been met with strong opposition from local groups (Alvares, 1987; Varghese, 2000; Dias, 2005; Menon and Ramana, 2007). One setting where opposition has been recorded consistently has been at public consultations to discuss Environmental Impact Assessments (EIA) of nuclear facilities, a necessary step for any project to be accorded environmental clearance. For example, at the first ever consultation to discuss a nuclear EIA in July 2001, of the nearly 30 members of the public who presented their views at the hearing, only one supported the project (Sri Raman, 2001; DOSE, 2001). Similar levels of opposition have been seen at other projects (Staff Reporter, 2005; Reporter, 2006; Menon and Ramana, 2007).

Unlike in the West, however, the reasons have less to do with concerns about safety or radioactive waste, though these do cause apprehension among locals. The vast majority of the population does not have any understanding about radiation and the associated hazards. A 1993 survey near the Kalpakkam nuclear complex, home to multiple nuclear reactors and other facilities, revealed that on average about 53 percent knew nothing about radiation, whereas a further 34.5 percent had some knowledge but were quite unclear (MAI, 1993). Rather, because of the much greater dependence on natural resources like land and water, the primary concern with nuclear facilities is their impact on lives and livelihoods. Reactors, for example, require cooling water and land, for which farmers compete, and discharge hot water and radioactive effluents into the sea, affecting fish workers. Similar factors also drive opposition to large hydroelectric dams, thermal power plants, and automobile factories.

The Future

Following the Nuclear Suppliers Group's exemption, Indian policy makers have been predicting their country will produce significant amounts of nuclear electricity in the future. The Ministry of Power, for example, hopes to add 40 GW of nuclear power by 2020, as a result of the US-India nuclear deal (MoP, 2008). This is a tall order by any scale. The most rapid growth of nuclear power in a single country has been in France, which added about 39 GW during the 1980s, or 3.9 GW/y (IAEA, 2009). That growth was based on a standard design, in contrast to DAE plans to import reactors with a range of designs. In the context of India's chequered history of nuclear power over the decades, such projections seem extremely ambitious.

One motivation behind making such large projections seems to be a need to hype up the demand for nuclear reactors and other technology so nuclear vendors will be tempted lower their prices in order to gain a foothold in a potentially large market. Lowered prices will be necessary if nuclear power is to compete in an Indian electricity sector that has been restructured over the last decade to promote competition. This process has resulted in increased sensitivity to electricity tariffs and costs of generation.

The major problem imported nuclear reactors will face is the high cost of electricity generation as a result of high capital costs, a factor that has increased in salience as estimated costs of new nuclear reactors mount. Recently completed domestic nuclear plants in India have cost around US$1,500/kW (2007 US dollars), though these were constructed before the observed price escalations in other countries (Bohra and Sharma, 2006).[23] The costs of LWR construction in other countries have been much higher. In March 2008, Progress Energy, a Florida utility, filed a Certification of Need document with the state's Public Service to construct two reactors, for which it estimates overnight construction costs of about US$5,000/kW for the first unit and US$3,300/kW for the second unit, with an average of about US$4,200/kW (NUKEM, 2008).

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[23] As explained earlier, even at this relatively low cost, they are not cost-competitive with domestic coal-based thermal plants.

The cost of the Olkiluoto reactor in Finland being constructed by Areva has been estimated at upwards of US$4,000/kW (at 2007 prices). It is fairly clear that imported nuclear reactors will be priced out of the Indian market.

This problem was recognized well before negotiations on the deal began. In the case of French reactors, M. R. Srinivasan, former head of the DAE, stated in 2003 that,

> Recent cost projections show that if an LWR were to be imported from France, the cost of electricity would be too high for the Indian consumer. This is because of the high capital cost of French supplied equipment. (Srinivasan, 2003)

Indian nuclear officials have set their hopes on licensed domestic manufacturing. In the words of Sudhinder Thakur, the executive director of the state-owned Nuclear Power Corporation, "When you build a reactor here, costs come down dramatically" (Jishnu, 2008). The chairman and managing director of NPC, S. K. Jain, says "India is pushing for a steady indigenisation of imported plants with the vendors" which "could go up to as much as 80 percent for future plants" (Chengappa, 2008). This is a strategy that finds favour with the domestic power industry. Companies such as Larsen & Toubro (L&T) and Bharat Heavy Electricals Limited (BHEL) have asked the Indian government to incorporate clauses for localization of imported reactor technology as part of the entry norms for foreign companies (Sasi, 2008). L&T from the private sector and BHEL from the public sector have historically been important suppliers to NPC's reactors. BHEL is also reportedly looking to join with Larsen & Toubro to build manufacturing capacity for both the conventional island and reactor portions of Light Water Reactors (Sasi, 2008). The two companies are also in talks with the four short-listed global reactor vendors.

It is not clear how far international nuclear vendors are willing to go down the route of localizing manufacturing in India. Lowered costs achieved by local manufacture in India would reduce profits and not allow for job creation efforts, despite promises made to the contrary by nuclear vendors in countries like the US and France as a reason to support the India nuclear deal. For example, in October 2008, as the US Congress approved the nuclear agreement, President George W. Bush stated that the deal "will strengthen our global nuclear nonproliferation efforts, protect the environment, create jobs and assist India in meeting its growing energy needs in a responsible manner" (Agencies, 2008). Further, the time it would take to set up manufacturing facilities in India would add to the already considerably long reactor construction periods. Therefore, vendors would obtain reduced profits, following a lengthy wait, and after substantial investments in Indian facilities. The growth of nuclear power, using imported reactors, is likely to be slow and limited. In the near term, however, there will at least be a few reactor purchases. As the price for shepherding the nuclear deal through the NSG, the Indian government seems to have promised the US, France, and Russia that it would purchase some nuclear reactors from them. At the US Senate Foreign Relations Committee hearings, Undersecretary William Burns stated that:

> The Indian government has provided the United States with a strong Letter of Intent, stating its intention to purchase reactors with at least 10,000 mega Watts (MW) worth of new power generation capacity from US firms… India has committed to devote at least two sites to US firms. (Varadarajan, 2008)

NPC has reportedly shortlisted four major reactor manufacturers: Westinghouse Electric Company with its Advanced Passive 1000 reactors; General Electric-Hitachi with its Advanced Boiling Water Reactor and Economical Simplified Boiling Water Reactors; Areva with its European Pressurized reactors; and Russia's Rosatom with its Vodo-Vodyanoi Energetichesky Reactor (VVER1000). The plan is to devote one site each to clusters of reactors from each vendor. Sites have been identified across the country.[24] At the first of these, Jaitapur, south of Mumbai, land acquisition efforts have already been initiated. This site seems to have been earmarked for Areva (Agencies, 2007). Another site that has been identified is Mithi Virdi in the western state of Gujarat, likely for a US vendor (Shah, 2008). At both sites, public protest against the proposed construction of reactors has commenced.

While the primary focus has been on importing reactors, there are also plans to export nuclear technology. In addition to the NPC, the state-owned BHEL is emerging as an important player. Following the establishment of a joint venture to manufacture 700 MW turbines, NPC and BHEL are reported to be in talks aimed at setting up a joint venture company to export Pressurized Heavy Water Reactors (Mehdudia, 2008). The process began in April 2008 when the two companies signed a memorandum of understanding to float a joint venture company for executing engineering, procurement and construction contracts for nuclear power projects in India and abroad (Bureau, 2008).

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[24] Two Russian VVER-1000s are already being constructed at the Koodankulam site in southern Tamil Nadu and further reactors imported following the NSG waiver will likely be constructed at the same site.

There seems to be widespread realization that, in view of the enormous costs involved, a large-scale expansion of nuclear power in India will require the involvement of the private sector. There has been interest in setting up nuclear reactors from large industrial houses like the Tatas and Reliance; however, there remain several uncertainties with regard to private companies, especially foreign ones, operating nuclear power plants in India.

The first uncertainty is whether private parties can be legally involved in this activity. The usual reading of the 1962 Atomic Energy Act is that it gave the central government power over all matters relating to atomic energy. It can exercise those powers either by itself or through any authority or corporation established by it or by a government company. The 1962 Act defines "Government Company" as a company in which not less than 51percent of the paid-up share capital is held by the central government. A liberal interpretation of the Atomic Energy Act, therefore, could be that the private sector can already participate in nuclear power generation with minority equity participation (Ram Mohan, 2009).

The government, however, seems not to interpret the act in this manner. In February 2009, Minister of Power Jairam Ramesh stated that the role for the private sector in the first phase of Indian nuclear power generation would be very limited, in view of issues relating to the safety, fuel and management aspects of nuclear power plants (Bureau, 2009). Even the country's largest government-owned power company, the National Thermal Power Corporation, which wanted to start operating nuclear power stations, could not do so by itself. It had to enter a joint venture with the Nuclear Power Corporation, in which the latter held a 51 percent stake (Bureau, 2009).

The second uncertainty is the question of liability. Under section 29 of the Atomic Energy Act, the government is not subject to legal proceedings for good faith actions taken in pursuance of the Act. Thus, a government-owned company, such as the Nuclear Power Corporation, would be protected from public claims in the event of an accident. This has been a source of concern to private vendors, especially in the US, who have been urging India to sign the international nuclear liability convention.

Breeder Reactors in the Future

Although the NSG waiver might result in India importing LWRs, in the longer term the DAE's projections are dependent on breeder reactors. The DAE's projection of 275 GW by 2052 includes 262.5 GW from breeders (Grover and Chandra, 2006). Not surprisingly these estimates are based on very optimistic assumptions that cannot be substantiated on the basis of historical experience. But even if one were to give the DAE the benefit of doubt, these projections are erroneous. The DAE has simply not accounted properly for the likely availability of plutonium (Ramana and Suchitra, 2009).

The performance of the one breeder reactor India currently operates, the FBTR, has been mediocre. Its construction was delayed as a result of sanctions following the 1974 nuclear test. Since it attained criticality, the FBTR has experienced numerous accidents and unusual occurrences (Suresh Kumar et al., 2002). It was 15 years before the FBTR managed more than 50 days of continuous operation at full power (Prasad, 2001). Over the first 20 years of its life, it has operated for only 36,000 hours, or only 20 percent of its life thus far (DAE, 2006: 16). The FBTR experience does not offer a good basis for optimism about Indian breeder performance.

The DAE's projections are primarily based on assumptions about doubling time – how long it would take a breeder reactor to produce enough plutonium to fuel a new breeder reactor core. 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 (Grover and Chandra, 2006).

As mentioned earlier, the DAE's methodology is flawed and does not account correctly for plutonium flows. To start, the base capacity of breeders assumed in 2022, which provides the basis for the 2052 projection, would require much more plutonium for startup fuel than the DAE will have at that time. The DAE does not currently have enough reprocessing capacity to handle the spent fuel produced by the heavy water reactors operating and under construction. Constructing new reprocessing plants typically takes ten to 15 years.[25] Even if the DAE manages to inexplicably obtain the necessary plutonium to construct its

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[25] The Thermal Oxide Reprocessing plant in the United Kingdom, with a capacity of 800 t/y, received government approval in 1978 but started operating only in 1992 (Forwood, 2008). More instructive is the case of the most recent commercial reprocessing facility, the Rokkasho plant in Japan, again with a capacity of 800 t/y. Built on the basis of the design already used for the French La Hague reprocessing plant, Rokkasho's construction commenced in 1993 (Walker, 2006). Construction was completed and tests began in 2006. As of December 2008, the ongoing delays were reportedly the result of numerous technical problems in the last stage of testing (Sawai, 2008). In India, the Kalpakkam Atomic Reprocessing Plant (KARP) facility, with a much smaller capacity of 100 t/y, received financial sanction in 1983 (DAE, 1987: 19), but was commissioned only in 1998 (DAE, 2000: 25).

projected reactor capacity with an equal quantity to spare, under the DAE's assumed rate of growth, the plutonium stockpile would be reduced by about 40 tons in the first ten years. This loss is the result of a three-year lag between the time a certain amount of plutonium is committed to a breeder reactor and when it reappears along with additional plutonium for refueling the same reactor, thus contributing to the start-up fuel for a new breeder reactor.

A more careful calculation, taking into account plutonium flow constraints, shows the capacity for breeders in 2052 would be at best about 40 percent of the DAE's projections (Ramana and Suchitra, 2009). If a more realistic out-of-pile time of three years were taken into consideration, India's breeder capacity in 2052 based on plutonium from PHWRs will drop to about 17 percent of the DAE's projections. The only constraint assumed here is fissile material availability. These calculations are based on assumptions that there will be no delays because of infrastructure 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.

Thorium

There is a lot of discussion in the literature on the Indian nuclear program about thorium-based breeders, the third stage of the three-phase strategy. However, even in the DAE's plans, these become significant only after 2052 (Grover and Chandra, 2006), primarily because of difficulties in dealing with the highly radioactive contaminant uranium-232 that is produced along with uranium-233, the fissile material produced from fertile thorium. Even if such reactors are constructed, they will likely have the same features that make plutonium-based breeders uneconomical: the need for reprocessing and the requirement for extensive safety precautions in fabricating fuel with uranium-233 if it is contaminated even at very low levels with uranium-232.

Conclusion

Nuclear power is likely to remain a major part of India's energy plan. Though it has had some success, notably the development of some expertise over most steps in the nuclear fuel chain, India's atomic energy program has not achieved any of its promises. The most important failure has been that after more than 60 years, nuclear power constitutes only three percent of the nation's electricity generation capacity. To some extent, this has been a result of international sanctions imposed on India after its nuclear weapon tests. An important lesson from this experience is that while export controls and other trade restrictions might not cause a nuclear program to completely shut down, sanctions may slow its growth.

The limited amount of nuclear electricity generated has been at a relatively high cost. The DAE's reactor construction costs have not dropped over the years and, despite their claims of improved construction practices, show little evidence of learning. The operational efficiencies of reactors have improved over the decades, however.

The DAE claims safety is its primary concern, but it has been a low priority, as demonstrated by India's history of small accidents, unsafe design choices and operating practices. The DAE's obsession with secrecy inhibits independent studies of the complex (Ramana, 2009). The agency in charge of regulating safety at nuclear facilities comes under the administrative control of the AEC, and is therefore not truly independent.

The effects of the NSG waiver remain uncertain. Though the DAE's nuclear reactor construction has been marked with time and cost overruns, overnight construction costs are cheaper than reactors sold on the international market, primarily because of lower labour costs, but also because licensing requirements are easier to meet. Nevertheless, nuclear electricity remains more expensive than coal-based thermal power that is and will remain the staple source of electricity in the country. Unless foreign countries offer cheap loans for purchasing imported reactors, India is unlikely to be able to afford them. Such financing is unlikely to be a viable means for large-scale expansion of nuclear power in India.

Despite media hype and continued government patronage, nuclear power is unlikely to contribute significantly to electricity generation in India for several decades. Apart from the high cost of the power it produces, one important factor that will reduce the potential contribution of nuclear power even further is the reliance on breeder reactors, a technology shown to be unreliable in most countries that have experimented with them. A shift to the more reliable light water reactors might increase nuclear power's contribution to electricity generation; however, in doing so, the nuclear establishment is faced with a dilemma. On the one hand, LWRs can be imported from the West at unit costs much higher than Indian PHWRs. This would make nuclear electricity uncompetitive. On the other hand, if the DAE were to insist on local manufacture of reactor components, as a way of leveraging India's lower labour costs, many of the construction projects might proceed slowly, as has been the case in the past. In any case, nuclear power will only contribute a modest share of electricity to India's energy needs for several decades at the very least.

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