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Nuclear Safety in India: Theoretical Perspectives and Empirical Evidence

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Abstract

This paper examines lessons from the operating experience in India's nuclear facilities about factors influencing the risk of potential accidents. Different perspectives on safety in hazardous facilities have identified organizational factors coincident with reliable and accident-free operations; these include functional redundancy and compensation for failures, the importance of organizational leaders in setting and maintaining safety standards, healthy relationships between management and workers, and sophisticated learning from failures. Using publicly available information about incidents and failures, we find that these conditions are frequently violated.

Introduction

India plans a large expansion of power from nuclear energy over the next few decades. Many reactors and other facilities associated with the nuclear fuel cycle, and operated by the country's Department of Atomic Energy (DAE) and its subsidiary organizations, have had accidents of varying severity (Ramana 2012).[1]

A major accident in a densely populated country like India can be catastrophic. Therefore, a study of the safety performance and culture in India's nuclear facilities is of inherent interest.

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In addition, if nuclear energy is to substantially contribute to reducing greenhouse gas emissions, it would have to expand significantly over the next few decades. Such expansion would especially have to occur in industrializing or developing countries with fast-growing electricity requirements and relatively low levels, or complete absence, of nuclear generation capacity. India offers a case study for understanding the challenges facing expansion of nuclear power in such countries. How India's nuclear establishment manages safety is therefore of interest not just to people living in India but to the larger international community.

A number of studies on nuclear safety have noted the importance of characteristics of the organizations managing and operating these facilities. The goal of this paper is to shed some light on the organizational culture and behavior within India's nuclear establishment. Our inquiry relies partly on the previous work of scholars of organizations, who have observed common behaviours in those organizations managing to operate hazardous technologies in a safe and reliable manner. On the basis of the examination of the safety record of India's nuclear facilities, we derive lessons about the prospects for safe operations therein. We also seek to understand how the choices made by the DAE and its everyday practices affect the risk of accidents at its facilities.

We begin by describing theories of accidents and safety that are relevant to our study, and examine the causal role that various factors can play. Then, we analyse two safety related incidents in Indian nuclear facilities. From the public record, the first event appears to be unique. However, the second incident that we analyse is one among a number of such events, and we examine some of the underlying reasons for why efforts to stop their recurrence have been unsuccessful. This examination points to lacunae in how nuclear facilities are managed. As further illustration of some underlying lacunae, we also list some other recurring failures at India's nuclear facilities. All of these problems suggest that the DAE's actions are inconsistent with actions recommended by safety theorists for lowering the risk of accidents. Finally we briefly discuss latent influences on organizational behaviour within the DAE, such as economic and political pressures as well as attitudes towards risk.

Theoretical Perspectives on Safety

The origins of accidents and factors contributing to safe operation have been discussed previously in the literature and we briefly summarize some of the different approaches to the subject. Broadly speaking, these approaches can be divided into those focused on aspects of the technology and those focused on aspects of the operating organization and management. One may further subdivide approaches focused on technology into those that are optimistic about avoiding accidents through the use of appropriate design, especially what is termed “defense in depth” (Glasstone and Sesonske 1981; Knief 1992); and those that are pessimistic about avoiding accidents, notably the school of thought that goes back to Charles Perrow’s analysis of what happened at the Three Mile Island nuclear plant in 1979 as a “normal accident” whose origins lay in the structural features of the system (Perrow 1984).[2] We do not delve into these approaches that are focused on technology because nuclear power in India is not significantly different from other countries in this aspect. In contrast, our case studies are revealing about the organizational behaviour in DAE’s facilities, where a country-specific examination merits interest owing to its unique institutional situation.

There is a vast literature on the origins of accidents that seeks to identify the organizational factors contributing to safe operation. In the context of nuclear hazards, much attention has been paid to the concept of safety culture, especially in the aftermath of the 1986 Chernobyl accident (Pidgeon 1991). A prominent example of approaching safety through the study of organizational practices has been the work of the High Reliability Organization (HRO) School, led by a group of scholars at the University of California, Berkeley. HRO scholars tried to explain what allowed some organizations to operate hazardous technologies with what they felt was “an extraordinary level of safety and productive capacity” (La Porte 1996). Their task was to identify those organizational factors that allowed the management of risky technologies with a relatively high degree of safety. The HRO group maintains, though, that they have only uncovered "conditions that were necessary for relatively safe and productive management of technologies" but do not wish to imply that "these conditions were sufficient" (La Porte and Rochlin 1994).

The common features of organizations with a record of relatively safe operation that HRO theorists identify involve: the importance of political elites and organizational leaders placing a high priority on safety in design and operations; setting and maintaining safety standards and practices; sophisticated learning from failures; and ensuring a healthy relationship between management and workers (Roberts 1989, 1990; LaPorte and Consolini 1991; Sagan 1993; La Porte 1996; Bigley and Roberts 2001). Other safety theorists identify similar factors. James Reason calls for an organizational culture where managers are knowledgeable and pay attention to safety in the organization as a whole, showing the ability to learn appropriate lessons from the safety information system and act upon those, and where the relationship between managers and workers encourages reporting of errors (Reason 1997, 195-196).

Redundancy in system operations, by making allowance for failures, is also widely emphasized. Because of the reliance on safety devices to ensure accident-free operations, all these perspectives, implicitly or explicitly, require organizations to ensure that that these devices should be reliable and built with high quality control. One approach that does not fit well into our dichotomy of technology-focused and organization-focused approaches is the Systems Safety (SS) approach (Leveson 2002, 2004; Marais, Dulac, and Leveson 2004; Leveson et al. 2009; Leveson 2011). Here, safety is an emergent property that can be evaluated only at the system level and not at the component level; and accidents do not necessarily result only from individual failures. In their view, accidents result from inadequate enforcement of constraints on behaviour (where the constraints can arise from the physical system, engineering design, management, or from regulatory practice) at each level of the socio-technical system (Leveson et al. 2009). However, SS theory too has implications for organizational behaviour in particular, it emphasizes tolerance for dissenting views and avoiding blame (Leveson 2011, 415-443), drawing in part on the notion of a "just culture" (Dekker 2007; Reason 1997).[3]

We do not select between these different perspectives on safety. Rather, we focus on what they share in their recommendations for increasing safety. We now examine two specific events at the DAE's facilities and evaluate how the organization performed with respect to these characteristics.

Safety Events in Indian Nuclear Installations

The presence or absence of severe accidents, or more generally the frequencies of accidents, do not by themselves point to underlying characteristics of a system: for example, whether it is safe or whether the managing organization acts to promote high reliability. Instead, following the observations of HRO scholars, we ask if the available evidence suggests a high priority to safety at all levels of the organization, whether the management is open to inputs from workers, and whether there are efforts to improve safety at all levels and to learn from mistakes. Some of the evidence on these questions emerges around accidents triggered by prosaic failures, which are likely to have been easily prevented if the practices had been different. There have been many such failures at Indian reactors and other nuclear facilities (Ramana and Kumar 2010; Ramana 2012). We now examine two in detail.[4] These are by no means the most severe accidents or the ones with greatest potential consequences,[5] but they clearly illustrate problems such as the failure to learn from experience of repeated failures, biased reporting and interpretation of accidents by management, lack of openness and transparency, low priority to worker safety, and inadequate attention to safety in general.

1. Kalpakkam Reprocessing Plant Accident

The DAE has three reprocessing plants to deal with irradiated spent fuel produced by nuclear reactors.[4] The reprocessing of spent fuel produces chemical and radioactive wastes, which are usually classified into low (LLW), intermediate (ILW) and high level waste (HLW) depending on the radioactivity level or concentration. In January 2003, a valve failure at the Kalpakkam Atomic Reprocessing Plant (KARP) led to HLW entering a stainless steel tank (Tank-3) intended to hold LLW. Six employees, who were instructed to collect samples from Tank-3, ended up collecting this highly radioactive material (Venkatesh 2003).

At the time of the valve failure, about five years after the plant started operations in 1998, no monitors had been installed to check for radiation levels in that area. Neither were there any mechanisms to detect the valve failure. Therefore workers had no way of knowing that the samples they went in to collect were emitting high levels of radiation. The accident was recognized only after a sample collected was taken to a different room and radiation measured. In the meantime the six workers had received extremely high radiation doses (280-420 mSv) (Anand 2003).

What is of greatest relevance to an evaluation of the safety culture of the DAE is the response of the management. KARP is administratively under the Bhabha Atomic Research Centre (BARC). Despite a safety committee's recommendation that the plant be shut down, the management of BARC decided to continue operating the plant (Anand 2003). Then, the employees union, the BARC Facilities Employees Association (BFEA), wrote a letter 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 higher officials had always cited urgency of operations as a reason for the Health Physics Department not following safety procedures. Once again there was no response from the management. Finally, 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; this had the desired effect, and two days later all the striking workers joined back. The BARC Director's interpretation was smug: "If the place was not safe, they would not have joined back" (Mohapatra 2003). Ultimately, the union leaked information about the radiation exposure to the press. Once the news had become public, the management grudgingly admitted that this was "worst ever radiation exposure incident" in its history (Das 2003).

But the management blamed the whole accident entirely on the employees. According to the Director of BARC, the accident was due to a "little bit of error in judgment, miscalculation and over-enthusiasm" on the part of employees (Radhakrishnan 2003). He went on to assert that "failure of equipment went unnoticed" in the facility. Finally, he went on to directly accuse the workers by suggesting that their "mistake was that they didn't mount area gamma monitors before entering the area" (Anonymous 2003). But there were no gamma monitors in that area. Indeed, installing such monitors had been one of the ten demands made in the BFEA letter to the management. Asked about this, the head of BARC's waste management division could only offer the excuse: "We were in the process of installing these when the unfortunate incident occurred" (Anand 2003), thus belying their own accusation.

The second accusation leveled by the management was that some of the workers were not wearing their thermoluminescent dosimeter (TLD) badges (Anand 2003). But this has nothing to do with the accident; TLD badges would not have warned the workers about radiation levels until after the fact.[5] They would only help assess each worker's radiation exposure after the event. Furthermore the fact that TLD badges were frequently not used suggests a low priority to radiation safety. For its part, the BFEA claimed that because of the unrelenting pace of work at KARP and "unsafe practices being forced on the workers", accidents have become a regular feature (PTI 2003). In other words, practices that promote safety had to be ignored in order to meet work pressures.[6] The accident, again, illustrates how the DAE violates most of the recommendations offered by the different perspectives on safety.

First, there was no redundancy that would protect the workers in case of valve failure. SS theorists argue that in addition to learning from an accident, there should be “an increasing emphasis on preventing the first one”, i.e., the focus should be on preventing precursor failures and other accident triggers (Leveson 2011, , 5).

Second, though the plant had been operating since 1998, there had neither been any monitors in the region to detect radiation levels, nor any procedures to alert workers to radiation levels. In organizational terms, this lack of redundant mechanisms to deal with valve failure and of monitors to detect such failure suggests the relatively low importance given to safety by the leadership.

Third, rather than trying to work with them to prevent the occurrence of events of this kind, the BARC management blamed the workers and took disciplinary action against employees who demanded information about the accident (Sri Raman 2003). More generally, KARP operations were marred by discontent and opacity, and the management repeatedly disregarded worker’s attempts to have safety features installed.

All of these might be contrasted with the findings of safety theorists. For example, the HRO school’s studies reveal that high performing nuclear power plants possess an atmosphere of openness and responsibility, “in which all individuals regardless of rank feel responsible for every detail of plant operation they can observe, and in which they feel free to point out their observations without fear of adverse consequences to themselves” (Rochlin and von Meier 1994). Such organizations “reward the discovery and reporting of error, without at the same time peremptorily assigning blame for its commissions. This obtains even for the reporting of one’s own error…” (La Porte 1996, , 64). Likewise, the Systems Safety approach posits that “blame is the enemy of safety” (Leveson 2011, , 56-57, 531). Finally, many safety theorists emphasize the importance of trust between workers and managers (Cox, Jones, and Collinson 2006), and this characteristic again is lacking at KARP. In a similar vein, James Reason has called for "an atmosphere of trust in which people are encouraged, even rewarded, for providing essential safety-related information"(Reason 1997, , 195).

2. Heavy Water Leaks

In March 1999, some personnel at the second unit of the Madras Atomic Power Station were using a device called BARCCIS (Bhabha Atomic Research Centre Channel Inspection System), which is used to inspect coolant tubes in reactors. Suddenly, a plug that sealed one of the coolant channels—through which heavy water was to flow and remove the heat produced during reactor operations—slipped away and a large quantity of radioactive heavy water leaked out.[7] Even though the reactor was shut down for maintenance, a plant emergency was declared, which could be seen as an indication of the seriousness of the event.

The station director's statement to the press, on the other hand, creates the impression that it was a scheduled release of heavy water: "We undertook the operation of re-seating the plug in the form of replacement which involves *planned escape* of heavy water from the channel inside the fuel machine vault" (Subramanian 1999) [our emphasis]. He went on to characterize the leaked heavy water as being of "an insignificant quantity."

A number of public statements by others associated with the nuclear programme, however, indicated that the amount was not insignificant. The secretary of the Atomic Energy Regulatory Board stated that it was less than 4 tons (Subramanian 1999, , 28). Soon afterwards, the Press Trust of India reported, quoting officials from the Nuclear Power Corporation, that it was about 6 tons (Xinhua 1999). A former chairperson of the AERB went further and speculated that about 14 tons of heavy water might have leaked and supported his speculation by asking, "Why was a plant emergency declared (during this period, the reactor was shut down)? If the leak was only like that from a tap, why declare a plant emergency?" (Subramanian 1999, , 28). Even the lowest of these estimates cannot be considered insignificant.

Leaks of heavy water at Indian nuclear power stations have been a regular occurrence, starting with the Rajasthan Atomic Power Station (RAPS)— the first heavy water reactor constructed in India (Ghosh 1996). But, despite a lot of effort—quite understandable because heavy water is expensive and hard to produce—the DAE has not managed to contain them. Just in 1997, such leaks occurred at the Kakrapar-I, Madras Atomic Power Station-II, and Narora-II reactors (IAEA 1998, , 301-320). In 2004, leaks at RAPS resulted in large release of tritium to the atmosphere (AERB 2009, , 37). The previous year, high levels of tritium were recorded in the liquid discharges from the Narora and Kakrapar Atomic Power Stations (AERB 2008, , 38).

There appear to be multiple causes for such heavy water leaks. On 2 July 2007, high tritium levels were detected at the RAPS-II reactor, which turned out to be because of a "pin-hole" opening in the primary heat transfer system. In turn, the opening was a result of a "substantial reduction in wall thickness due to flow induced erosion/corrosion" (AERB 2008, , 19-20). During January to March 2009, there were three heavy water leaks in different nuclear reactors, all due to "fretting damage" [a special wear process that occurs at contact areas] (GoI 2010, , 33). A heavy water leak in the Madras Atomic Power Station in 1988-89 was due to the failure of the moderator inlet manifolds, a device meant to withstand the impact of the moderator heavy water entering the calandria at high velocity (Sundararajan, Parthasarathy, and Sinha 2008, , 95).

The amounts of heavy water that leak can be significant. For example, on 15 April 2000, there was a leak involving seven tons of heavy water at the Narora-II reactor (AERB 2001, , 13). Three years later, on 25 April 2003, there was another heavy water leak at the same reactor, this time involving six tons (AERB 2004, , 18).[8] In contrast, leaks at Canada's heavy water reactors involve much less quantities, typically tens or at most hundreds of liters.[9]

Following the 1999 heavy water leak, the Atomic Energy Regulatory Board undertook a review of the BARCCIS system and suggested a number of changes in design, operating procedures, and training (AERB 2004, , 18). The occurrence of numerous heavy water leaks since, including a leak at the Narora reactor that was similar in character to the MAPS leak, despite these changes suggests weaknesses of regulation, failure to learn from earlier accidents, or continued operator errors.

3. Problems with equipment maintenance, design and practice

Heavy water leaks are not the only recurring problem in the DAE's facilities. Another frequent issue is with inadequate and inoperative safety equipment. These are required to maintain control of the reactor under unanticipated circumstances, so if they are not working there is an increased probability that an initial event could cascade. A related problem is of safety devices being left in an inoperative state or maintenance of equipment being neglected. There are examples in the case of the Narora reactor, which experienced an accident in 1993 when turbine blade failure led to a fire in the turbine building and a complete loss of power in the station; and operators had to intervene in multiple ways to shutdown the reactor, avoid recriticality and facilitate decay heat removal; details of this accident has been discussed elsewhere (Ramana and Kumar 2013; Ramana 2012; Ramana and Kumar 2010). During this accident, the smoke sensors in the power control room at Narora did not detect the fire as soon as it started (Srinivas 1993); the fire was detected only when the flames were noticed by plant personnel.[10] Similarly, three hours and fifty minutes into the accident, the two operating diesel driven fire water pumps failed due to causes that have not been identified (Nowlen, Kazarians, and Wyant 2001). A third pump was out of service for maintenance.

Two contributing factors to the Narora accident in 1993 had also been prevalent in DAE's facilities: excessive vibrations in the turbine bearings and oil leaks. In 1981, Rajasthan-2 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, the reactor had to be shutdown yet again when a large oil leak from the turbine governing system was observed. Only when the reactor was restarted a third time, in early 1982, were the high vibrations of the turbine bearings and the failure of the turbine blades noticed (IAEA 1983, , 250). This then led to a prolonged shutdown of more than 5 months. Even after this problem had apparently been fixed, the reactor had to be shutdown 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 (Madras-1) was shutdown repeatedly because of high bearing vibrations in the turbine generator (IAEA 1986, , 240). Rajasthan-1 had to be shutdown due to high bearing vibrations in 1985, 1989, and 1990 (IAEA 1986, , 242; 1990, , 302; 1991, , 298).

Oil leaks were also common. In 1988, Madras-2 was shutdown due to an oil leak from the generator transformer (IAEA 1990, , 288). In 1989, a heavy spark was observed from slip rings on the exciter end of the turbine in Madras-1; 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 Madras-2 in 1989 (IAEA 1990, , 300). In 1992, there was an oil leak in the turbine stop valve in Madras-2 (IAEA 1993, , 288). In addition in 1992, in the Narora-1 reactor there were two separate oil leak incidents in the turbine generator system (IAEA 1993, , 289). There has been at least one hydrogen gas leak prior to the Narora fire accident: in 1991, in the generator stator cooling water system of Madras-2 (IAEA 1992, , 390).

All these failures should have caused serious concern because the factors that combined to produce the Narora accident in 1993 had combined elsewhere earlier to disable all the safety systems. In 1989, a reactor in Spain experienced turbine vibrations, which caused oil to leak and hydrogen to escape. The hydrogen burned violently and the oil caught fire. The fire spread through the cabling and disabled operation of the emergency cooling and heat exchange pumps (Ramsey and Modarres 1998, , 325). The reactor was permanently shutdown.

Another set of examples of repeated failures in DAE facilities involves failures of heat transport pumps. In 1980, Rajasthan-1 experienced unanticipated shutdowns four times during power system fluctuations; at least thrice this happened after the disabling of primary heat transport pumps, and heat generated during operation could not be removed from the core (IAEA 1981, , IN-3, 3). At least once, some pumps were already inoperative when power fluctuations caused additional pumps to fail. That year in Tarapur-2 generation was restricted for nearly two weeks because only one recirculating pump was in service (IAEA 1981, , IN-2, 3). Subsequently that year, the unit had to be shutdown for 12 days to attend to the failure of the sole recirculating pump.[11] Such problems recurred through the 1980s and 1990s. In 2004, Madras-2 was shutdown for 8 days because the two main primary coolant pumps were unavailable (IAEA 2005, , 324). After being restarted, the reactor had to be shutdown again because motor bearings of one of the pumps had to be replaced.

These examples indicate that organizational elites pay insufficient attention to small failures, and also to maintenance and inspection. Lack of attention to such factors has been identified as one of the underlying causes of the 1988 Piper Alpha accident (Paté-Cornell 1993). In that sense, these failures also indicate inadequate attention to safety by the DAE's leaders to safety in design and operations. SS theorists argue that there should be "an increasing emphasis on preventing the first one", i.e., the focus should be on preventing precursor failures and other accident triggers (Leveson 2011, , 5). The public record does not suggest any such increased emphasis.

The other problem that the continuing series of small leaks and other failures offers evidence of is the inability to engage in sophisticated learning from failures. James Reason points out that an organization with good safety culture "must possess a learning culture—the willingness and the competence to draw the right conclusions from its safety information system" (Reason 1997, , 196). As discussed earlier, because of the recurrence of similar failures despite avoidance efforts, there is reason to question the competence of the DAE. A further problem might be a tendency to simplify interpretations, a tendency that safety theorists warn against (Vogus and Welbourne 2003). For example, After the 1999 leak, the Director of the Madras Atomic Power Station claimed that it "did not involve an unusual situation" and that the amount of heavy water that escaped "was only an insignificant quantity"; the Secretary of AERB stated, "the safety of the reactor was ensured" (Subramanian 1999). This is unlike how HROs operate. Weick *et al* observe that while "most organizations tend to localize failure, effective HROs tend to generalize it" (Weick, Sutcliffe, and Obstfeld 1999).

Conclusions and Discussion

By studying organizations that operate hazardous technologies, safety theorists have identified various factors that are common to organizations that manage to operate these facilities in a manner that is relatively free of errors. Our case studies suggest that the Indian Department of Atomic Energy does not possess all of these characteristics, and goes against some of the recommendations offered by a number of safety theorists. Specifically, we find evidence of political elites and organizational leaders not placing a high priority on safety in design and operations. For example, at the Kalpakkam Reprocessing Plant, there was clearly inadequate redundancy to protect against valve failure, and no radiation monitors to detect that highly radioactive waste had entered an area that was not designed to deal with the material. The DAE also does not appear to be learning the appropriate lessons from failures and this is demonstrated both through repeated failures and by its benign interpretations of events. After the heavy water leak at the Madras Atomic Power Station, the director tried to dismiss the significance of the leak in multiple ways. The KARP management drew wrong lessons about the safety of the facility from the fact that striking employees rejoined work. Finally, there is evidence that the relationship between management and workers is strained, with employees being blamed for failures that they could not possibly be responsible for.

It is clear that there is much to be gained by the DAE developing these organizational characteristics that are prescribed by safety theorists. The question that emerges is whether there are factors that decisively work against the acquisition of such characteristics.

Unlike many utilities running nuclear plants that have been studied in the safety literature, the DAE is a state owned ("public sector") organization. Thus, in contrast with private companies, profitability is not an overarching goal. However, the DAE has frequently stated that it aims to produce economical nuclear power. There are several instances where economic motivations have been cited as a motivation to cut back on activities promoting safety.[14] Furthermore during various phases in its five-decade long experience with operating reactors and other nuclear facilities the DAE has been under pressure, in part because of its inability to meet production targets it set itself, to accelerate construction, reduce maintenance time for reactors, and cut costs. In this, there may be some parallels with organizations such as the National Aeronautics and Space Administration (NASA) in the United States (Leveson et al. 2009). Thus, pressures on the DAE to prioritize efficient and economical delivery of its products, i.e., nuclear electricity and or related services, over improving safety might have weighed against the adoption of practices followed at HROs. These measures, while offering the benefit of safe operations, are expensive, especially in labor and management resources, and these might be seen as unproductive and not worth the cost if facilities are perceived by management to have been operating smoothly for many years (Pool 1997, , 277).

A second important factor that might work against the DAE adopting practices more conducive to lowering risk is the confidence that the DAE seems to have that the facilities that it builds and operates are completely safe. For example, in the aftermath of Fukushima the head of the DAE asserted that nuclear reactors [in India] are "one hundred percent" safe, and the Chairman of the Nuclear Power

Corporation went as far as denying what happened in Fukushima: "There is no nuclear accident or incident in Japan's Fukushima plants. It is a well planned emergency preparedness programme which the nuclear operators of the Tokyo Electric Power Company are carrying out to contain the residual heat after the plants had an automatic shutdown following a major earthquake" (PTI 2011b). Some months later, the head of the DAE asserted that the probability of a nuclear accident at the DAE's reactors is "one in infinity", seeming to imply zero (PTI 2011a).

Complacency and discounting of risks has been observed to be one of the root causes of many accidents (Leveson 2011). Scott Sagan identifies overconfidence within the U.S. nuclear weapon complex as a "serious problem" (Sagan 1993). One of the lessons learnt through the analysis of a 2001 accident in the Netherlands was the importance of avoiding over confidence and "to avoid relying on a past successful history" (Mengolini and Debarberis 2012). Organizations where "past good performance is taken as a reason for future confidence (complacency) about risk control" has been identified as a weakness (Hale and Heijer 2006, , 136). James Reason points out that 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"; HROs, on the other hand, "seem excessively bleak" (Reason 2000). There is plentiful evidence that the DAE is anything but bleak when it considers the safety of its facilities. Overconfidence is likely to have a causal effect on safety, and therefore might be an important source of problems in the DAE's facilities.

In summary, we have offered evidence here of instances of accidents and failures of safety systems at the DAE's facilities, as well as organizational characteristics that violate the recommendations of safety theorists. This combination suggests that the DAE does not meet the demanding organizational requirements for safe operations of a complex, high hazard technology. Our analysis of two safety related events shows some of these problems, including the repeated occurrences of accidents triggered by prosaic failures in its facilities, poor organizational learning from previous failures and system elites not being sufficiently interested in safety and not listening to employees. These factors together have been identified as playing a causal role in improving safety, and their absence makes accidents in DAE facilities more likely.

The organizational weaknesses of the DAE are a reminder of how hard it is to establish a strong safety culture. India's nuclear power programme dates back to 1948, when its Atomic Energy Commission was first established; its first power reactor started operating in 1969. At the institutional level, it seemed to be paying attention to safety regulation by establishing bodies to oversee the various facilities in the country ever since the constitution of an internal Safety Review Committee in 1972 (Gopalakrishnan 2002, , 384-385). Numerous documents verbalize the importance of safety culture and the DAE has benefited from reviews by international bodies like the World Association of Nuclear Operators (Koley et al. 2006; GoI 2007). If, despite these efforts, there are ongoing and serious concerns about the safety of nuclear facilities in India, the problems would magnify if nuclear power were to expand manifold. If nuclear power is seen as an important part of the solution to climate change, this should be borne in mind, especially in the context of countries with limited experience of nuclear power. It also prods us to reiterate a popular adage in the nuclear industry: a nuclear accident anywhere is a nuclear accident everywhere.

Notes:

1. Examples of such subsidiary or affiliated organizations are the Nuclear Power Corporation of India Limited (NPCIL), the Bhabha Atomic Research Centre (BARC), and the Indira Gandhi Centre for Atomic Research (IGCAR). Safety regulation is the responsibility of the Atomic Energy Regulatory Board (AERB), except for those facilities that have potential nuclear weapons applications, including fuel cycle facilities such as reprocessing plants. Since its inception, the AERB has reported to the AEC, which is headed by the operational head of the DAE. Following the Fukushima accidents, there have been widespread expressions of concern about the safety of Indian nuclear facilities, including the AERB's

lack of independence. As a result, the Indian government has proposed changing this arrangement. In this paper, we use DAE as an umbrella term to refer to all these subsidiary organizations. We recognize that the events described in this paper are classified as incidents according to the International Atomic Energy Agency's International Nuclear Event Scale, but deliberately use the more commonly used term accidents in order to emphasize that all these events have safety significance, especially when studying organizational culture.

2. Since then, Perrow's work has spurred an enormous range of analyses of a variety of systems (Sagan 2004).
3. A just culture provides "an atmosphere of trust in which people are encouraged, even rewarded, for providing essential safety-related information—but in which they are also clear about where the line must be drawn between acceptable and unacceptable behaviour" (Reason 1997, , 195).
4. To the extent possible, we derive these descriptions from documents put out by the DAE and its sister organizations. If these are not available, or as a supplement, we use news and media reports. We assume that these are being accurate unless there is some strong reason to not believe that. Another source of information has been the detailed annual reports entitled "Operating Experience with Nuclear Power Stations in Member States" that the International Atomic Energy Agency (IAEA) puts out. These reports are based entirely on information that the DAE provides the IAEA.
5. That distinction probably befits the 1993 fire at the Narora atomic power station.
6. This does not include pilot-scale reprocessing plants and hot cells.
7. These badges measure cumulative exposure over a period of time, and are meant to be submitted to the health physics department for assessment.
8. It may be mentioned that, from the limited public information available, Indian reprocessing plants appear to have generally operated at low efficiencies (IPFM 2010).
9. The heavy water loaded in a reactor becomes radioactive because some of the deuterium (heavy hydrogen) nuclei absorb a neutron to become tritium (a hydrogen atom with two neutrons). Further, this tritium will be

in the form of tritiated water, which is easily absorbed by the body as it is chemically identical to water.

10. On 28 June 2007, Narora II experienced a heavy water leak (AERB, 2008, 38). In June and July of 2012, there were two significant heavy water leaks at the Rajasthan Atomic Power Station, one involving radiation exposure to 38 workers (Sebastian, 2012; Sundaram, 2012).

11. See for example, http://ca.news.yahoo.com/300-litres-heavy-water-spilled-point-lepreau-124018967.html

12. This problem continues to recur. In 2005, for example, the Atomic Energy Regulatory Board (AERB) found instances of failures in fire detectors at Kakrapar and power supply for emergency cooling at Madras (PTI 2005).

13. Another recurring problem at this reactor are leaks from a primary feed water pump recirculation line.

14. For example, the Tarapur I & II reactors suffered regularly from vibrations, but the DAE chose not to make design and other changes to eliminate these vibrations "for economic reasons" (Nanjundeswaran and Sharma 1986).

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