


Nuclear Submarines in South Asia: New Risks and Dangers

Zia Mian ^a, M.V. Ramana ^b and A.H. Nayyar^a

^aProgram on Science and Global Security, Princeton University, Princeton, NJ, USA; ^bSchool of Public Policy and Global Affairs, University of British Columbia, Vancouver, Canada

ABSTRACT

The South Asian nuclear race is moving to sea, with India's government announcing that it has successfully put nuclear weapons at sea, and evidence suggesting that Pakistan is preparing to do so. This article traces India's decision to deploy nuclear-powered submarines, some armed with nuclear weapons, and the debate in Pakistan on the utility of nuclear-armed submarines and the possible acquisition of nuclear-powered submarines. The article then reviews the global history of submarine accidents, especially those where nuclear-powered submarines were involved, and looks in particular at the consequences of a potential naval reactor accident where radioactivity might be released into the environment. Such naval reactor accidents constitute a major but unappreciated challenge associated with the deployment of nuclear submarines in addition to new pathways for escalation to nuclear war that are more widely recognized.

ARTICLE HISTORY

Received 21 December 2018
Accepted 13 May 2019

KEYWORDS

Nuclear weapons; nuclear submarines; India; Pakistan; accidents

Introduction

In November 2018, India's Prime Minister Narendra Modi announced that an Indian nuclear-armed and nuclear-powered submarine had successfully completed its "first deterrence patrol" (Outlook Web Bureau 2018). In so doing, India has followed the example of the United States, Russia, the United Kingdom, France and China, all of whom operate nuclear-powered and nuclear-armed submarines. Pakistan, for its part, is pursuing plans to put nuclear weapons at sea on submarines as part of its nuclear posture. While Pakistan's navy does not have any nuclear-powered submarines, it has started preparing to put nuclear-armed cruise missiles on conventional submarines and may seek a nuclear-powered submarine capability of its own.

These developments create new additional paths by which conflict between India and Pakistan, who have already fought four wars, might escalate deliberately or inadvertently to nuclear war. These dangers add to the already fraught security landscape of South Asia (Mian and Ramana 2014; Ramana and Mian 2014; Hoodbhoy 2012; Ramana and Rammanohar Reddy 2003; Bidwai and Vanaik 1999). Many analysts have highlighted the many ways in which the move to sea has introduced a further element of instability into a region that has already experienced many military crises (Joshi and O'Donnell 2014; Rehman 2015; Clary and Panda 2017).

CONTACT Zia Mian  zia@exchange.Princeton.EDU  Program on Science and Global Security, Princeton University, Princeton, NJ, USA

© 2019 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group on behalf of the Nagasaki University. This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

An issue that has received much less attention is the risk of accidents involving nuclear-powered submarines. The need for more focus on this problem was made vivid in a January 2018 report that India's first domestically built nuclear-powered submarine, the INS Arihant, had been taken out of service over ten months earlier after an accident while in port (Peri and Joseph 2018). Although the veracity of this report has been questioned (Unjhawala 2018), India's submarines have been in other accidents (Datta and Borwankar 2013; Zee Media Bureau 2014; Pubby 2017), making the possibility of nuclear submarine accidents a reasonable concern.

This article starts with an exploration of the emergence of India's nuclear-powered submarine program and the accidents it has experienced so far, and the debate in Pakistan on deploying nuclear weapons on submarines and to move to acquire nuclear-powered submarines. It then reviews the global history of submarine accidents and especially those involving nuclear-powered submarines. It looks in particular at the consequences involving a naval reactor accident where radioactivity might be released into the environment. Finally, it briefly explores the new risks of escalation of conventional conflicts into nuclear ones that result from the introduction of nuclear-armed submarines.

India's Nuclear Submarines

The Indian navy has had a long interest in submarines, acquiring its first submarine in 1967 in a deal with the Soviet Union. India used its submarines as part of its naval operations during the 1971 war with Pakistan. Two submarines were deployed in the Arabian Sea and one in the Bay of Bengal with the mission to "attack and sink all Pakistani warships" and "to sink all merchant shipping sighted/detected when specifically ordered" and "patrol and surveillance" (Kohli 1989, 82). In the end, they took part in no actual combat.

The Indian navy also has had a fifty-year-long interest in nuclear propulsion; as long ago as 1968, navy engineers were sent for training in nuclear science, which led in 1976 to a team of naval engineers being assigned to the Department of Atomic Energy's Bhabha Atomic Research Center to work on nuclear propulsion options and then in 1981 to an agreement for assistance from the Soviet Union in developing naval nuclear propulsion (Anand 2016). This Russian help seems to have been crucial to India's naval reactor project. According to one report, "Scores of Russian engineers were sent to India . . . to aid the Department of Atomic Energy (DAE) and the Defence Research & Development Organisation (DRDO). It was the Russians who supplied the vital designs, precision equipment based on their VM-5 reactor, and the technology of miniaturising the reactor" (Bidwai 2009). India's former Chief of Naval Staff has confirmed that Russia was "the main source of technology" for the nuclear submarine project (Aroor 2009).

India's first land-based submarine nuclear reactor prototype went critical in 2003. The first nuclear submarine to be designed and built in India was the INS Arihant, which was launched in July 2009 and whose reactor went critical in 2013. According to the head of India's navy in 2010, the INS Arihant was supposed to have been commissioned in 2012 and to begin "deterrent patrol" (Unnithan 2010). The submarine finally began what were described as "sea acceptance trials" in December 2014, having earlier "passed its harbor acceptance trials" (TNN 2014). The Arihant was commissioned in August 2016.

In addition to the INS Arihant submarine, a second nuclear submarine has been ready to undergo tests since 2012 and a third vessel has been under construction (Anandan 2012). India seems to be planning on a fleet of four nuclear-powered submarines to be armed with ballistic missiles carrying nuclear warheads. The third and fourth vessels are planned for launch by 2020 and 2022, and “final design work” has started on the follow-on generation of ballistic missiles submarines (Unnithan 2017). India has long had the capability for producing the highly enriched uranium required as nuclear reactor fuel for the submarine (Ramana 2004). This uranium enrichment capacity is being systematically increased (Cloughley and Kelley 2014; IPFM 2015).

The Arihant submarine is intended to carry up to 12 ballistic missiles each armed with one nuclear warhead. Currently, this missile is the B05, also known as the K-15, with a range of 700–750 kilometers. Naval planners want submarine-launched missiles with longer ranges to be deployed. Vice Admiral Ravi N. Ganesh, who headed the Indian nuclear submarine building programme for four years, states “the INS *Arihant* and her successors will need to be armed with missiles of at least intermediate ballistic missile range (3,000–5,500 km). Until a missile with this range becomes operational, India’s sea-based deterrent must clearly be considered to be in a developmental stage” (Ganesh 2014). The process of building such longer-range missiles has started. The first test of a 3000 kilometer range submarine-launched ballistic missile named K-4 was carried out in March 2014 (Daily Bhaskar 2014). The Arihant submarine is reported to be capable of carrying four of these (compared to twelve of the shorter range K-15 missiles) (Bagla and Som 2014).

The Indian navy in 2012 leased for ten years a nuclear attack submarine from Russia (Sen 2012). This submarine (INS Chakra) does not carry nuclear weapons but has likely been deployed with the Arihant during its tests. In December 2014, India decided to lease another nuclear submarine from Russia, again in the same class and with the same conditions, including not using it as a platform for nuclear weapons (Sen 2014).

In February 2015, India’s government approved the construction of six nuclear-powered attack submarines (Pandit 2015). The program’s cost has been estimated to be about 1 trillion Rupees (Bipindra 2015). Work on the attack submarines project started in 2017, with Chief of Naval Staff Admiral Sunil Lanba declaring in December “It has kicked off and I will leave it at that. It is a classified project. The process has started. I will not comment further” (PTI 2017).

India’s development of its naval capability appears to be driven in part by a long-standing attempt to demonstrate nuclear arsenal capabilities associated with states currently seen as great powers (the United States, Russia, Britain, France and China) as well as a more immediate strategic competition with China, with control of the Indian Ocean being a particular area of contention (Singh 2015). From December 2013 to February 2014, a Chinese nuclear-powered attack submarine traveled from China through the Strait of Malacca into the Indian Ocean passed by Sri Lanka on its way to the Persian Gulf and then returned home (Page 2014). An almost identical area of operations for the Indian Navy was described in 2017 by its Chief of Staff Admiral Lanba who observed that “regular deployment of naval ships and aircraft is being maintained in the North Arabian Sea, Gulf of Oman, Persian Gulf, the Andaman Sea and the approaches to the strategically important straits of Malacca, Lombok and Sunda” (Lanba 2017).

Admiral Lanba also revealed that “The Indian Navy is at the threshold of joining a select league of navies capable of providing Submarine Search and Rescue in the Indian Ocean Region with two Deep Submergence Rescue Vessel Systems scheduled for induction next year” (Lanba 2017). India’s growing submarine capabilities make it a more valuable ally for the United States in its efforts to counter China’s growing military power. The United States and India have been conducting joint naval exercises for a long time now, but increasingly these are described in terms such as “moderating China’s increasingly assertive behavior” and current and retired members of India’s navy have publicly disclosed their concerns about the “deployment of Chinese submarines, warships and tankers in the Indian Ocean” (Raghuvanshi 2017). The 2018 naval exercises were focused on “anti-submarine operations” (Pubby 2018).

The development of these nuclear submarines is in line with the model of nuclear weapons development that India has followed after the May 1998 nuclear tests. Much of this has been based on the draft nuclear doctrine released by the National Security Advisory Board in 1999 (NSAB 1999). This doctrine calls for India’s nuclear forces to be deployed on a triad of delivery vehicles of “aircraft, mobile land-based missiles and sea-based assets” that are structured for “punitive retaliation” so as to “inflict damage unacceptable to the aggressor”. Submarines clearly fall under the third category of “sea-based assets”, although that term also allows for different kinds of naval nuclear weapon systems to be acquired. The emphasis on a triad means that the development of a nuclear submarine capability is unlikely to result in India stopping further development of its land-based missiles or acquisition of nuclear-capable aircraft.

Pakistan’s Debate About Nuclear Submarines

The Pakistan navy acquired its first submarine in 1964, three years before India. The PNS Ghazi was the recommissioned USS Diablo, which had first entered service in 1945 in the United States navy. It saw service in both the 1965 and 1971 India–Pakistan wars, and in the latter conflict sailed around India to the naval base at Vishakhapatnam intent on harassing the Indian aircraft carrier INS Vikrant, which it failed to find. According to a Pakistani account, in early December 1971 PNS Ghazi “probably misjudged her position and doubled back into her own mine field, thus setting off a mine that she laid for the enemy. The mine blew and cracked open her forward torpedo room ... The submarine sank with all crew onboard. at a distance of about 1.5 nautical miles from Vishakhapatnam breakwater” (A. Ahmed 2017).

The current Pakistani submarine fleet consists of two Agosta-70 diesel-electric vessels bought from France and commissioned in 1979–1980, and three Agosta-90B diesel-electric vessels purchased in 1994, one of which was made in France, the second assembled in Pakistan, and the third made entirely in Pakistan (Pakistan Navy n.d.). The third of these Agosta 90B submarines was fitted with the French MESMA air-independent propulsion system and by 2011 the other two vessels of this class had been retrofitted with this system (Osman 2015). In 2016, Pakistan signed a deal with Turkey for these submarines to be upgraded (Staff Reporter 2016).

In 2016 also, Pakistan signed a deal with China for buying eight Yuan class diesel-electric attack submarines (Nauman and Page 2015; Globsec 2016). It is reported that China will build four of the submarines at Karachi Shipyard, and that China will also

transfer submarine construction technology to Pakistan (Syed 2015). These submarines will include the air-independent propulsion system. The submarines are expected to be completed between 2023 and 2028 at an estimated cost of up to \$5 billion (HT Correspondent 2016).

Pakistan announced the setting up of a Naval Strategic Force Command headquarters in 2012, indicating an intention to put nuclear weapons at sea. The indications are these weapons will be nuclear-armed cruise missiles on some of its current submarines. In 2018, Pakistan announced the successful underwater test launch of the Babur, a 450 km range cruise missile, which had its first test in 2017 (Staff Reporter 2018). Pakistan's Inter-Services Public Relations (ISPR) described this result as "the successful attainment of a second strike capability" (Sial 2018). Given Pakistan's efforts to match India, it is unlikely that the acquisition of a nuclear-armed submarine will lead to any reductions in its land-based nuclear-armed missile forces.

Pakistan also may be wanting to build a nuclear-powered submarine. In 2005, the head of Pakistan's navy Admiral Shahid Karimullah said "Pakistan will have to make nuclear submarine itself because no one will give it to us. Our conventional capabilities are less than India. We have no nuclear submarine However, by 2015 we will be able to come at the level of India" (HT 2005). It was not clear, however, whether this claim referred to the development of a nuclear-armed submarine or a nuclear-powered submarine. A former vice admiral in the Pakistan Navy has argued that Pakistan must build nuclear-powered and nuclear-armed submarines of its own (Naqvi 2012).

It is recognized that this may not be possible for Pakistan to do alone. In 2010, a former Pakistan Navy commander argued that to match India, Pakistan should plan "either to lease nuclear submarines or eventually development [of] its own, or both" and that in particular, Pakistan should seek an arrangement with China for "the training and subsequent lease of a nuclear-powered submarine. The PLAN's (Peoples Liberation Army Navy's) Xia submarine could be an appropriate start. A pool of selected Pakistan Navy officers could be trained to operate an SSBN, with theoretical/academic work ashore followed by operational training at sea and finally a strategic deployment" (M. A. Khan 2010).

General Khalid Kidwai, who for 15 years served as the head of Pakistan's Strategic Plans Division, which is responsible for Pakistan nuclear weapons, in March 2015 addressed the issue of Pakistan having nuclear submarines (Lavoy 2015). He noted the need for a - "modern second strike capability for Pakistan" and observed that:

I would say it's a work in progress. It's a work in progress where different elements, and different segments will come, are coming in stages. And there will be a time when there will be a platform as well. There will be a time when there will be a weapon. There will be a time where there will communications part of it coming into place. I can say with confidence that we are not too far away from it. So, comprehensively speaking I think this capability will come into play in the next few years.

There are signs of some public support for a nuclear-powered submarine program in the media. One newspaper editorial in 2018 argued, "We must also develop programmes to build sophisticated and advanced indigenous submarines, ultimately leading to the production of nuclear submarines" (Editorial 2018).

Meanwhile, there are reports of "long-standing rumors of an indigenous nuclear powered submarine" (M. Ahmed 2014). Media reports continue to suggest Pakistan was

planning or had started work on a nuclear powered submarine (Ansari 2012). One media report claims that the Pakistan Atomic Energy Commission (PAEC) has been working on “a project ‘to design and manufacture a miniaturized nuclear power plant for a submarine’” since 2001 (Detsch 2013). It is possible this may so far be limited to work on a land-based prototype for a naval reactor. Pakistan may seek and receive help from China in such a project.

A Troubling History of Submarine Accidents

There is a long history of submarines and submarine accidents. A survey of submarine losses over 200 hundred years (1774–1985) found that 1750 submarines had been lost by a total of 23 nations, with 1448 submarines lost because of enemy action and 302 submarines lost because of some kind of accident or error (Gray 1996, 250).

One study of 60 years (1946–2005) of submarine accidents which led to the vessels being sunk or significantly damaged found that the “greatest source of loss for submarines was a flood (21%) followed closely by collision (18%)” (Tingle 2009). Other major causes were explosions and fires. The analysis found that “the causes behind collisions involve human factors (operator error and/or an aggressive party) or a less-than-adequate capability to effectively detect (or be detected as the situation warrants) and quickly maneuver to avoid striking”. It also found that a large share of submarine sinking events took place within the first 10 years of its operation.

A number of these accidents have involved nuclear submarines (Arkin and Handler 1989; Nilsen, Kudrik, and Nikitin 1996; Gray 2003). The nature of accidents experienced by nuclear-powered submarines globally has been varied, but nearly half of them were related to nuclear reactors (Nilsen, Kudrik, and Nikitin 1996). They are listed in [Appendix 1](#), together with their causes and casualties. Of the total of 41 accidents recorded in 36 submarines, 12 related to nuclear reactors, resulting in the release of radioactivity within the vessel as well as in the sea, and radiation poisoning as well as the death of the crews in some cases. Other accidents involved non-nuclear explosions, fires, flooding, running aground, etc. Over 650 crew members died in these accidents. In many cases, the entire crew sank with the submarines.

There have also been quite a few accidents that involved the nuclear reactor, arguably the accident type that is most specific to nuclear-propelled submarines like Arihant, including loss of coolant accidents (LOCAs) and criticality accidents (Compton et al. 2003; Takano et al. 2001). Many of these accidents have resulted in radioactive materials being released to the biosphere, usually under water but also sometimes into the air (IAEA 2001).

The largest number of nuclear-powered submarine accidents occurred with the Soviet/Russian submarines. The first three accidents with nuclear power submarines took place in the period from 1960 to 1962 and involved Soviet vessels and in all cases were due to problems with nuclear reactors. These accidents were:

- In October 1960 the November class K-8 submarine suffered a loss of coolant accident, which led to the leakage of radioactive gases, exposing a number of crew members to radioactivity, although there is no report of any radiation-related deaths. The submarine continued to be in service after repairs and clean-

up. Ten years later, in 1970, the same submarine had a fire on board and sank with 88 crewmen.

- In July 1961, the ballistic missile carrying nuclear submarine K-19 also suffered a loss of coolant accident and a core melt down in its reactor, leading to a heavy contamination of parts of vessel, again exposing crew to radioactive contamination. Eight crew members died immediately while 14 others died of radiation poisoning over the next two years. The reactor was removed and dumped in the sea together with the damaged fuel.
- In June 1962, the nuclear-powered submarine K-3 had a serious malfunction in the reactor in which the core was seriously damaged. The reactor was again removed and dumped in the sea with the damaged fuel.

In fact, of the 14 nuclear reactor-related accidents on submarines, 13 occurred with Soviet/Russian vessels. Six suffered loss of coolant accidents, five had uncontrolled start-up due to operator errors, while in nine of the accidents, the reactor core was damaged.

Problems with naval nuclear reactors are not confined to Russia and have continued after the Cold War. A 2011 declassified report by the UK Ministry of Defence's senior nuclear safety expert warned that "Current UK practice falls significantly short of benchmarked relevant good practice", with the submarine reactors "potentially vulnerable to a structural failure of the primary circuit" which could cause "a release of highly radioactive fission products" and lead to "a significant risk to life to those in close proximity and a public safety hazard out to 1.5 km from the submarine" (Edwards 2011). Safety failures on the part of the UK Ministry of Defence have continued and the ministry "has been formally reprimanded by its internal safety regulator for five nuclear safety breaches" between 2010 and 2017 (Edwards 2018).

The ongoing problems of safety in countries that have operated nuclear submarines for decades lend themselves to the possibility that South Asia too will run the risks of accidents involving submarines carrying nuclear weapons.

Reasons for Concern about Safety

There is both empirical and theoretical cause to be concerned about accidents involving nuclear submarines. Nuclear submarines are complex technical artifacts operating under challenging conditions. As highlighted by several theorists, nuclear weapons-related systems, because of their structural characteristics, can pose unavoidable risks of accidents (Perrow 1984; Sagan 1993). Both the submarine and a nuclear reactor are, individually, technologies that are susceptible to a range of accidents. Add to this ballistic missiles and nuclear warheads, and the combination of failures in a nuclear ballistic missile submarine that could result in devastating consequences multiplies dramatically. All of these are to operate deep under water, with limited supplies of air and water, possibly under enemy fire. The problems with safety culture in organizations that deal with nuclear and defence related artifacts increase this structural conditions for risk.

Empirically, the main reason to be concerned about the safety of nuclear submarines in South Asia is that even during the short period of experience, there have been a few accidents involving India's nuclear submarine fleet already. In December 2017, INS

Chakra had an accident. The cause was given as “either a collision at sea or accidental scraping while entering the narrow channel into the naval base at Vishakhapatnam” and fixing it was reported to require “substantial repair work” (Pubby 2017). The accident suggests that the Indian naval authorities might not be paying adequate attention to safety because it is reported that the “Visakhapatnam harbour has recorded incidents in the past when warships have touched the bottom while navigating the tight water channel. In January 2014, the INS Airavat – a Shardul class amphibious warship – suffered damage to its port propeller while entering the harbour” (Pubby 2017).

There is some evidence that Arihant, the latest nuclear submarine to be deployed, has already been in an accident. According to one report, “a hatch on the rear side was left open by mistake while it was at harbour” and that as a result “Arihant’s propulsion compartment was damaged after water entered it” (Peri and Joseph 2018). But this report has been questioned (Unjhawala 2018), and India’s defense ministry refused to answer a question asked in Parliament about the extent of the damage and the cost of repairs (PTI 2018).

Even one of the nuclear submarines under construction has been in an accident. In March 2014, “the hatch of a ‘tank’ to be installed in INS Aridhaman – the follow-on submarine to the first one, INS Arihant – blew off” during routine tests, leading to one worker’s death and injury to two others (Pandit 2014). An unnamed officer told the press that the accident “would have been catastrophic if it had happened inside the submarine” (Pandit 2014).

There is also evidence of poor safety culture in India’s civilian nuclear facilities and in the Bhabha Atomic Research Centre, the main organization involved in India’s nuclear weapons program (Ramana 2012; Ramana and Kumar 2010). There is ample evidence for the occurrence of “accidents and failures of safety systems” at these facilities and of “organizational characteristics that violate the recommendations of safety theorists” and therefore, there are doubts about whether these institutions can “meet the demanding organizational requirements for safe operations of a complex, high hazard technology” (Kumar and Ramana 2013, 64).

There have also been a host of accidents involving military equipment, in particular aircraft. One tally of these lists over 2000 accidents involving the Indian Air Force’s airplanes since the 1930s (Bharat Rakshak 2019). Over a hundred of these have involved airplanes that could carry nuclear weapons. These accidents again relate to deficiencies in the safety culture of the Indian-armed services (Mian 2003).

Accidents and Their Consequences

The consequences of an accident at a nuclear submarine will, of course, depend on the kind of accident that occurs. Perhaps the most severe accident experienced so far involved the nuclear reactor itself and occurred on the morning of 10 August 1985 at a dockyard in Chazhma Cove near Vladivostok in what was then the Soviet Union (now Russia). Docked there was an K-431 (originally called K-31, and with the NATO reporting name of Echo II class) Soviet nuclear-powered submarine whose two reactors had just been refilled with fresh fuel (Hoffman 1998). The following day “workers found leaks from the seal of the upper lid” and to fix it, they:

lifted up the upper lid but they did not drain the water of the primary loop, neither did they detach the lattice, which was used to keep control rods in place. When the upper lid was raised for a few centimeters, a navy torpedo boat swept by, that created a big wake. The wake rocked the refueling service ship and its long crane arm resulting in rapid withdrawal of all control rods. The rapid reactivity insertion caused a huge power pulse followed by steam explosion.

Due to the explosion, the 12 t[on] upper lid and all of fuel assemblies were blown out from the reactor compartment and the submarine pressure hull was destroyed . . .

Immediately after the explosion, a fire broke out which was brought under control after 4 h[ours]. Due to the fire, radioactive materials were released continuously from the damaged submarine for 7 h and contaminated the area within 50–100 m[etres] from the submarine. The explosion killed eight officers and two workers instantly. About 2,000 workers participated in terminating the accident and in decontamination. Among these workers, 290 workers were exposed to radiation of more than 50 mSv [milli Sievert, a unit of radiation dose], including 10 workers with acute radiation sickness. (Takano et al. 2001, 146–48)

Several points are worth noting in this description. First, the accident involved an unanticipated chance occurrence, in particular, the wake from the torpedo boat that resulted in control rods being withdrawn and the setting off of an uncontrolled chain reaction. Such initiators are at the root of many a nuclear accident and cannot be predicted in advance. Therefore, it is impossible to protect against them with certainty. Second, the accident resulted in an explosion that was powerful enough to disperse the radioactivity contained in the fuel. Third, the accident did not stop with just an explosion but led to a secondary fire that led to further damage.

Though significant, the radioactive release from the accident was relatively small because the “spontaneous chain reaction occurred in fresh fuel which was just loaded in the reactor and had not yet operated in the nuclear reactor. Consequently, there were no fission products from previous operation in the reactor” (Sivintsev 2003, 422). The situation could have been very different if the accident had happened when the reactor was still loaded with irradiated fuel.

The second factor that ameliorated the impact of the accident was that it occurred in a relatively sparse area. The areas nearest to the accident site that have relatively high population densities are in Japan, the Korean peninsula, and parts of China; all are a hundred to a thousand kilometers from Chazhma Cove.

In South Asia, on the other hand, this is unlikely to be the case. The new naval base in Rambilli is located in Vishakhapatnam district in eastern India with a population density of 384 persons per square kilometer (Census Organization of India 2016). The city of Vishakhapatnam is but 50 km away (Patnaik 2016; Shukla 2014), and had a population of over 1.7 million people (population density of 3,240 per square kilometer) according to the 2011 census.

If an accident such as the 1985 one described above occurred in this naval base, the consequences could be severe. The radiation dose to the population will be dependent on a number of factors, including the submarine’s operating history (which determines the radioactive inventory of the reactor) and the weather conditions. The inventory of Cesium-137, the most significant long-term contaminant in the case of nuclear reactor

accidents, in a submarine reactor could be approximately around 1 quadrillion Becquerels (1 PBq) if the fuel is fully irradiated (Compton et al. 2003, 7; Reistad and Ølgaard 2006, 32; Takano et al. 2001, 150). Much of this could be dispersed in the event of a criticality accident.

In a case study of a hypothetical accident at a waste tank at the Kalpakkam reprocessing plant, the dispersal of 30 PBq of Cesium-137 was found to result in nearly 97,000 excess cancers that would develop over decades in the exposed population, with about 47,000 fatalities (Ramana, Nayyar, and Schoeppner 2016). This result is in part due to much of the Cesium-137 being deposited in the densely populated city of Chennai. Correcting for the lower population density of Vishakhapatnam and its surroundings, the dispersal of roughly 1 PBq of Cesium-137 might result in roughly a thousand incidences of cancer in excess of the background rate, with a little less than half of them being fatal.

It is worth recalling in this regard that concern about risks from accidents involving nuclear-powered naval vessels as well as nuclear-armed vessels among New Zealand anti-nuclear movements led to a national decision in 1984 that in effect denied such vessels entry to its ports, which became law with the New Zealand Nuclear Free Zone, Disarmament and Arms Control Act of 1987 (Reitzig 2006). It was revealed in 1991 by Reg Farmer, Chair of the United Kingdom's Warship Safety Committee, that the United Kingdom had banned its nuclear-powered submarines from visiting foreign ports because of risks of reactor-accidents (Thames Television 1991). The United Kingdom, in addition to the UK Ministry of Defense's on-site emergency plans, has specific domestic regulations (UK Radiation Emergency Preparedness and Public Information Regulations) that apply in the cities of Portsmouth and Southampton because nuclear-powered submarines may port in those locations (Portsmouth & Southampton City Councils 2018; Health and Safety Executive 2018). These city plans are public documents. There is no information concerning similar naval reactor accident emergency preparedness plans in India. Such an emergency plan for cities that may have nuclear-powered submarines dock should be developed and made public.

The Potential for Escalation in South Asia

Nuclear submarines are dangerous in part because they are powered by nuclear reactors but also because some of them carry nuclear weapons. The nuclear-powered submarines that India has leased from Russia do not carry nuclear weapons but the Arihant and its successors are all designed to carry nuclear weapons. In the case of Pakistan, as discussed above, there are plans to deploy nuclear-armed cruise missiles on diesel-powered submarines.

Nuclear-armed submarines increase the potential for nuclear war because they open up new risk pathways. One pathway, often overlooked, stems from fact that "the sea is the only area where nuclear weapon platforms [of adversary states] ... actually come into physical contact" and this contact can lead to accidents from several kinds of what seem to be typical naval operations, including "covert submarine operations", "routine monitoring activities", "games of chicken [in which] each captain attempts to gauge the resolve of the other" and "harassment for tactical military purposes" (Ball 1985, 4). There already have been incidents of Indian and Pakistani naval platforms coming into

physical contact, for example, in 2011 when the Pakistani vessel PNS Babur brushed past India's INS Godavari (Hindu 2011).

The consequences of such events could be worse if such contact between submarines occurs during periods of heightened tensions or crises. During such periods, there may be inadvertent attacks on submarines carrying nuclear weapons because these are intermingled with submarines carrying only conventional weapons. Such concerns have been explored in the context of the Cold War between the United States and the Soviet Union, as well as in the US–China context (Posen 1992; Twomey 2011; Christensen 2012). Some notable instances occurred during the Cuban Missile Crisis, when US ships used practice depth charges against Soviet nuclear-armed submarines and almost led to the use of nuclear weapons (Burr and Blanton 2002).

One scenario that demonstrates how nuclear-armed submarines increase the potential for nuclear war between Pakistan and India emerged in early 2019. On 7 January 2019, the Indian Navy commenced a large military exercise involving dozens of ships and aircraft that was to last until 10 March 2019. Following a suicide attack on 14 February 2019 on an Indian military convoy in Kashmir, India and Pakistan ordered air strikes into each other's territory; an Indian plane was shot down and the pilot captured. On 27 February 2019, the Pakistani Prime Minister Imran Khan summoned and chaired a meeting of the National Command Authority – the body that oversees the country's nuclear warheads. Following the attack in Kashmir, the “major combat units of the Indian Navy including the Carrier Battle Group with INS Vikramaditya, nuclear submarines and scores of other ships, submarines and aircraft swiftly transited from exercise to operational deployment mode”, according to an official statement (Indian Navy 2019). The use of the plural suggests that Arihant, possibly with a nuclear-armed missile, and a nuclear submarine leased from Russia may have been among those deployed.

For their part, Pakistan's navy announced that it had detected an Indian submarine trying to enter Pakistan's territorial waters. A spokesperson from Pakistan's Navy announced, “The submarine could have been easily engaged and destroyed had it not been Pakistan's policy to exercise restraint in the face of Indian aggression and to give peace a chance to prevail. However, the submarine is being kept under watch along with monitoring of other Indian navy units. The detected submarine is one of the latest submarines of Indian navy” (Siddiqui 2019).

The possibility that Pakistan might have attacked an Indian submarine, even possibly one that is nuclear armed, should cause great concern. Had there been a Pakistani attack, either at the order of the higher authorities or by some officer on the ship, on a nuclear submarine, such as the Arihant, that would almost definitely lead India to escalate its operations, possibly involving the use of nuclear weapons. This might be justified by pointing to the attack on its own nuclear weapons.

Contact between the navies of India and Pakistan might also result from deliberate attempts to attack submarines. Both countries are known to be acquiring anti-submarine warfare capabilities (Web Staff 2016; Deepak 2017; Hayes 2018). India and the United States have held talks on anti submarine warfare, citing the growth in Chinese submarine activities in the Indian Ocean (Miglani and Torode 2016). Such developments make it more likely that during some underwater confrontation Indian or Pakistani or Chinese submarine personnel might feel compelled to launch their nuclear missiles in a “use them or lose them” scenario.

The introduction of nuclear-armed submarines, whether diesel fueled or nuclear fueled, increases the likelihood of conventional conflicts escalating to a nuclear one. Any use of nuclear weapons would have devastating consequences, especially if the use of nuclear weapons by one country sets off a nuclear response from the other side.

Conclusion

As India and Pakistan deploy nuclear weapons on submarines, the arms race in South Asia is moving into the sea and is creating a new set of dangers. These have to do with hostile and accidental encounters with nuclear-armed vessels and also nuclear-powered vessels, especially submarines. One concern that we have outlined in the paper is the possibility of a conventional conflict escalating into a nuclear one inadvertently. During the military crisis in South Asia in February 2019, India did put its nuclear submarines on alert and the Pakistani navy did try to intercept an Indian submarine, although likely not a nuclear one. However, the situation could have been much more serious had such an interception involved a submarine carrying nuclear weapons. A second concern involves reactor accidents on nuclear-powered submarines, which have severe impacts to public health and the environment because of the potential for radioactive releases. As we have detailed in this paper, there is both historical precedent and theoretical cause to be concerned about such accidents.

Acknowledgments

The authors are thankful to the editors and reviewers for useful comments and helpful suggestions. We are grateful to Robert Green for the transcript of the Reg Farmer interview .

Disclosure Statement

No potential conflict of interest was reported by the authors.

Notes on Contributors

Zia Mian is a physicist with Princeton University's Program on Science and Global Security, which is part of the Woodrow Wilson School of Public and International Affairs. He also directs the Program's Project on Peace and Security on South Asia. He is co-author with Harold Feiveson, Alexander Glaser, and Frank von Hippel of *Unmaking the Bomb: A Fissile Material Approach to Nuclear Disarmament and Nonproliferation* (MIT Press, 2014). He is the recipient of the 2014 Linus Pauling Legacy Award and the 2019 Leo Szilard Award from the American Physical Society.

M.V. Ramana is the Simons Chair in Disarmament, Global and Human Security at the Liu Institute for Global Issues in the School of Public Policy and Global Affairs, University of British Columbia and the author of *The Power of Promise: Examining Nuclear Energy in India* (Penguin Books, 2012) and co-editor of *Prisoners of the Nuclear Dream* (Orient Longman, 2003). He is a member of the International Panel on Fissile Materials and the Global Council of Abolition 2000. He is the recipient of a Guggenheim Fellowship and a Leo Szilard Award from the American Physical Society.

A.H. Nayyar is a visiting researcher at Princeton University's Program on Science and Global Security, which is part of the Woodrow Wilson School of Public and International Affairs. He works with the Project on Peace and Security on South Asia. He has taught in the Department of Physics, Quaid-i-Azam University, Islamabad and was Visiting Professor of Physics, Lahore University of Management Science, Lahore. He is a recipient of the 2010 American Physical Society's Joseph H Burton Award.

ORCID

Zia Mian  <http://orcid.org/0000-0002-0802-2306>

M.V. Ramana  <http://orcid.org/0000-0003-1332-930X>

References

- Ahmed, A. 2017. "Ghazi – The Prowler of the Deep." *Defence Journal* 20 (11): 65–66.
- Ahmed, M. 2014. "Trends in Technological Maturation and Strategic Modernization: The Next Decade." In *Nuclear Learning in South Asia: The Next Decade*, edited by F. H. Khan, R. Jacobs, and E. Burke, 58–70. Monterey, CA: Naval Postgraduate School. https://my.nps.edu/documents/104111744/106151936/5+Nuclear+Learning_Ahmed.pdf/5b46434b-4f40-4f32-9d83-618f8a6f7a68
- Anand, A. 2016. "Nuclear Propulsion in India." In *Submarine Propulsion – Muscle Power to Nuclear*, edited by A. Anand, 85–130. Mumbai: Frontier India.
- Anandan, S. 2012. "Second Nuclear Submarine Headed for Year-End Launch." *Hindu*, January 14. <http://www.thehindu.com/news/national/article2798864.ece>
- Ansari, U. 2012. "Pakistani Navy to Develop Nuclear-Powered Submarines: Reports." *Defence News*, February 11. <http://www.defensenews.com/article/20120211/DEFREG03/302110003/Pakistani-Navy-Develop-Nuclear-Powered-Submarines-Reports>
- Arkin, W. M., and J. Handler. 1989. "Naval Accidents: 1945–1988." Neptune Papers No. 3. Washington, D. C.: Greenpeace & Institute for Policy Studies.
- Aroor, S. 2009. "Admiral Arun Prakash: The Arihant in Perspective." *Livefist* (blog). September 18. <https://www.livefistdefence.com/2009/09/admiral-arun-prakash-arihant-in.html>
- Bagla, P., and V. Som. 2014. "This is INS Arihant, First Made-in-India Nuclear Submarine." *NDTV.Com*, August 20. <http://www.ndtv.com/india-news/ndtv-exclusive-this-is-ins-arihant-first-made-in-india-nuclear-submarine-651097>
- Ball, D. 1985. "Nuclear War at Sea." *International Security* 10 (3): 3–31. doi:10.2307/2538940.
- Bharat Rakshak. 2019. "Aircraft Losses Database." The Indian Air Force, Indian Army and Indian Naval Aviation. April 1. <http://www.bharat-rakshak.com/IAF/Database/Accidents/>
- Bhaskar, D. 2014. "3,000 km-Range SLBM Successfully Test-Fired by DRDO." *Daily Bhaskar*, May 13. <http://daily.bhaskar.com/news/NAT-TOP-3000-km-range-slbm-successfully-test-fired-by-drdo-4611759-NOR.html>
- Bidwai, P. 2009. "Sinking Billions into Nuclear Weapons." *Rediff News*, August 3. <http://news.rediff.com/column/2009/aug/03/sinking-billions-into-nuclear-weapons.htm>
- Bidwai, P., and A. Vanaik. 1999. *South Asia on a Short Fuse: Nuclear Politics and the Future of Global Disarmament*. New Delhi: Oxford University Press.
- Bipindra, N. C. 2015. "India Said to Approve Expansion of Submarine Fleet." *Bloomberg.Com*, February 18. <http://www.bloomberg.com/news/articles/2015-02-18/india-said-to-approve-richest-naval-expansion-in-five-years>
- Burr, W., and T. S. Blanton. 2002. "U.S. And Soviet Naval Encounters during the Cuban Missile Crisis." Electronic Briefing Book No. 75. Washington, DC: National Security Archive. <https://nsarchive2.gwu.edu/NSAEBB/NSAEBB75/>

- Census Organization of India. 2016. "Visakhapatnam (Vijayanagaram) District Population Census 2011, Andhra Pradesh Literacy Sex Ratio and Density." Census 2011. <http://www.census2011.co.in/census/district/130-visakhapatnam.html>
- Christensen, T. J. 2012. "The Meaning of the Nuclear Evolution: China's Strategic Modernization and US-China Security Relations." *Journal of Strategic Studies* 35 (4): 447–487. doi:10.1080/01402390.2012.714710.
- Clary, C., and A. Panda. 2017. "Safer at Sea? Pakistan's Sea-Based Deterrent and Nuclear Weapons Security." *Washington Quarterly* 40 (3): 149–168. doi:10.1080/0163660X.2017.1370344.
- Cloughley, B., and R. Kelley. 2014. "India Increases its Uranium Enrichment Programme." *IHS Jane's* 360, June 20. <http://www.janes.com/article/38957/india-increases-its-uranium-enrichment-programme>
- Compton, K. L., V. Novikov, F. Parker, and Y. Sivintsev. 2003. "The Radioactive Legacy of the Russian Pacific Fleet Operations and its Potential Impact on Neighboring Countries." Monograph IR-03-009. Laxenburg, Austria: International Institute for Applied Systems Analysis. <http://pure.iiasa.ac.at/7072/>
- Datta, S., and V. Borwankar. 2013. "While We Can Hope for the Best, We Have to Prepare for the Worst: Navy Chief DK Joshi." *Daily News & Analysis*, August 14. <https://www.dnaindia.com/mumbai/report-while-we-can-hope-for-the-best-we-have-to-prepare-for-the-worst-navy-chief-dk-joshi-1874239>
- Deepak, J. 2017. "Spoil for Choice." *Force India*, December. <http://forceindia.net/cover-story/spoil-for-choice/>
- Detsch, A. 2013. "Pakistan's Oversized Submarine Ambitions." *The Diplomat*, October 9. <https://thediplomat.com/2013/10/pakistans-oversized-submarine-ambitions/>
- Editorial. 2018. "Strengthening Pakistan Navy." *Pakistan Observer*, January 18. <https://pakobserver.net/strengthening-pakistan-navy/>
- Edwards, R. 2011. "Flaws in Nuclear Submarine Reactors Could Be Fatal, Secret Report Warns." *The Guardian*, March 10, sec. World news. <https://www.theguardian.com/world/2011/mar/10/royal-navy-nuclear-submarine-reactor-flaws>
- Edwards, R. 2018. "Ministry of Defence Rapped for Five Nuclear Safety Breaches." *The Ferret*, November 4. <https://theferret.scot/ministry-defence-nuclear-breaches/>
- Ganesh, R. 2014. "Political Stability First, Strategic Stability Second." *The Interpreter* (blog), October 14. <http://www.lowyinterpreter.org/post/2014/10/14/Stabilising-role-of-SSBNs.aspx>
- Globsec. 2016. "Pakistan - Hangor - Type 41 Yuan-Class New Submarines." *Globalsecurity.Org*. October 15. <https://www.globalsecurity.org/military/world/pakistan/ss-new.htm>
- Gray, E. 1996. *Few Survived: A Comprehensive Survey of Submarine Accidents and Disasters*. London: L. Cooper.
- Gray, E. 2003. *Disasters of the Deep: A History of Submarine Tragedies*. Third revised ed. London: Leo Cooper.
- Hayes, P. 2018. "Off the Beach: Underwater Warfare in the 21st Century." *Global Asia* 13 (1): 48–54.
- Health and Safety Executive. 2018. *Radiation (Emergency Preparedness and Public Information) Regulations 2001*. <http://www.hse.gov.uk/radiation/ionising/reppir.htm>
- Hindu. 2011. "INS Godavari Damaged in PNS Babur Manoeuvres." June 24, sec. *National*. <https://www.thehindu.com/news/national/INS-Godavari-damaged-in-PNS-Babur-manoeuvres/article13847710.ece>
- Hoffman, D. 1998. "Reactor Blast Shows Danger Of Aging Subs." *The Washington Post*, November. <https://www.highbeam.com/doc/1P2-691959.html>
- Hoodbhoy, P. 2012. *Confronting the Bomb: Pakistani and Indian Scientists Speak Out*. Karachi: Oxford University Press.
- HT. 2005. "Pakistan Navy Chief Says 'We Will Make Nuclear Submarines on Our Own.'" *Hindustan Times*, September 1.
- HT Correspondent. 2016. "China Confirms Sale of 8 Attack Submarines to Pak, First Delivery by 2023." *Hindustan Times*, October 21. <https://www.hindustantimes.com/world-news/china->

- confirms-sale-of-8-attack-submarines-to-pakistan-first-delivery-by-2023/story-kqSiZxhkB6r60QvhF2G7CK.html
- IAEA. 2001. "Inventory of Accidents and Losses at Sea Involving Radioactive Material." IAEA-TECDOC-1242. Vienna: International Atomic Energy Agency.
- Indian Navy. 2019. "Naval Commanders' at Kochi for Operational Discussions." March 17. <https://www.indiannavy.nic.in/content/naval-commanders-kochi-operational-discussions>
- IPFM. 2015. *Global Fissile Material Report 2015*. Princeton, NJ: International Panel on Fissile Materials.
- Joshi, Y., and F. O'Donnell. 2014. "India's Submarine Deterrent and Asian Nuclear Proliferation." *Survival* 56 (4): 157–174. doi:10.1080/00396338.2014.941574.
- Khan, M. A. 2010. "S-2: Options for the Pakistan Navy." *Naval War College Review* 63 (3): 85–104.
- Kohli, S. N. 1989. *We Dared: Maritime Operations in the 1971 Indo-Pak War*. New Delhi: Lancer International. <http://catalog.hathitrust.org/api/volumes/oclc/23261912.html>
- Kumar, A., and M. V. Ramana. 2013. "Nuclear Safety in India: Theoretical Perspectives and Empirical Evidence." *OUCIP Journal of International Studies* 1 (1): 49–72.
- Lanba, S. 2017. "Navy Day Press Conference at New Delhi: Full Address of Admiral Sunil Lanba." *India.Com*, December 1. <https://www.india.com/news/india/navy-day-press-conference-at-new-delhi-opening-address-by-admiral-sunil-lanba-chief-of-the-naval-staff-2702185/>
- Lavoy, P. R. 2015. *A Conversation With Gen. Khalid Kidwai*. Washington, D. C. <http://carnegieendowment.org/files/03-230315carnegieKIDWAI.pdf>
- Mian, Z. 2003. "A Nuclear Tiger by the Tail: Problems of Command and Control in South Asia." In *Prisoners of the Nuclear Dream*, edited by M. V. Ramana and C. Rammanohar Reddy. New Delhi: Orient Longman.
- Mian, Z., and M. V. Ramana. 2014. "Asian War Machines." *Critical Asian Studies* 46 (2): 345–360. doi:10.1080/14672715.2014.898459.
- Migliani, S., and G. Torode. 2016. "Wary of China's Indian Ocean Activities, U.S., India Discuss Anti-Submarine Warfare." *Reuters*, May 1. <https://www.reuters.com/article/us-india-usa-submarines-idUSKCN0XS1NS>
- Naqvi, T. H. 2012. "Indian Nuclear Submarine Programme." *The Nation*, May 12. <https://nation.com.pk/13-May-2012/indian-nuclear-submarine-programme>
- Nauman, Q., and J. Page. 2015. "Pakistan to Buy Eight Chinese Submarines." *Wall Street Journal*, April 2.
- Nilsen, T., I. Kudrik, and A. Nikitin. 1996. "The Russian Northern Fleet." 2: 96. Oslo: Bellona Foundation. <http://spb.org.ru/bellona/ehome/russia/nfl/nfl8.htm>
- NSAB. 1999. *Draft Report of National Security Advisory Board on Indian Nuclear Doctrine*. New Delhi: National Security Advisory Board. <http://mea.gov.in/in-focus-article.htm?18916/Draft+Report+of+National+Security+Advisory+Board+on+Indian+Nuclear+Doctrine>
- Osman, A. 2015. "Pakistan's Tool of War: Agosta 90B, Our Submarine in the Deep." *Dawn*, October 19. <http://www.dawn.com/news/1213256>
- Outlook Web Bureau. 2018. "INS Arihant Successfully Completes First Deterrence Patrol: PM Modi." *Outlook*, November 5. <https://www.outlookindia.com/website/story/ins-arihant-successfully-completes-first-deterrence-patrol-pm-modi/319636>
- Page, J. 2014. "China's Submarines Add Nuclear-Strike Capability, Altering Strategic Balance." *Wall Street Journal*, October 24, sec. Page One. <http://www.wsj.com/articles/chinas-submarine-fleet-adds-nuclear-strike-capability-altering-strategic-balance-undersea-1414164738>
- Pakistan Navy. n.d. "Submarine Force History." Pakistan Navy Official Website. N.D. https://www.paknavy.gov.pk/submarine_history.html
- Pandit, R. 2014. "Post-Accident, Lens on Nuclear Submarine Projects." *The Times of India*, March 10 <http://timesofindia.indiatimes.com/india/Post-accident-lens-on-nuclear-submarine-projects/articleshow/31758017.cms>.
- Pandit, R. 2015. "Govt Approves Construction of 7 Stealth Frigates, 6 Nuclear-Powered Submarines." *The Times of India*, February 18. <http://timesofindia.indiatimes.com/india/Govt-approves-construction-of-7-stealth-frigates-6-nuclear-powered-submarines/articleshow/46281364.cms>

- Patnaik, S. 2016. "GRSE, Reliance Facilities in City to Strengthen Navy's Capabilities." *The Hindu*, January 18. <https://www.thehindu.com/news/cities/Visakhapatnam/GRSE-Reliance-facilities-in-city-to-strengthen-Navy%E2%80%99s-capabilities/article14005124.ece>
- Peri, D., and J. Joseph. 2018. "INS Arihant Left Crippled after 'Accident' 10 Months Ago." *The Hindu*, January 8. <https://www.thehindu.com/news/national/ins-arihant-left-crippled-after-accident-10-months-ago/article22392049.ece>
- Perrow, C. 1984. *Normal Accidents: Living with High Risk Technologies*. New York: Basic Books.
- Portsmouth & Southampton City Councils. 2018. "Reactor Emergency Plan." *Version 2.0. Portsmouth & Southampton City Councils*. <https://www.portsmouth.gov.uk/ext/documents-external/cou-reactor-emergency-plan-v2.0-jul18.pdf>
- Posen, B. R. 1992. *Inadvertent Escalation: Conventional War and Nuclear Risks*. Ithaca, NY: Cornell University Press.
- PTI. 2017. "India Begins Project To Build 6 Nuclear-Powered Submarines." *NDTV.Com*, December 1. <https://www.ndtv.com/india-news/india-begins-project-to-build-6-nuclear-powered-submarines-1782555>
- PTI. 2018. "Information on INS Arihant Damage Cannot Be Divulged: Government." *Zee News*, March 28. <http://zeenews.india.com/india/information-on-ins-arihant-damage-cannot-be-divulged-government-2094382.html>
- Pubby, M. 2017. "India's Only Nuclear Submarine Damaged by Accident." *The Print*, October 3. <https://theprint.in/report/accident-damages-indias-only-n-powered-submarine-cracks-appear-in-sonar-dome/11450/>
- Pubby, M. 2018. "Season of Naval Exercises: Guam, RIMPAC, Trilateral." *Economic Times*, June 5. <http://economictimes.indiatimes.com/articleshow/64457495.cms>
- Raghuvanshi, V. 2017. "US, India and Japan Launch Joint Naval Exercises to Keep China in Check." *Defense News*, July 11. <https://www.defensenews.com/air/2017/07/11/us-india-and-japan-launch-joint-naval-exercises-to-keep-china-in-check/>
- Ramana, M. V. 2004. "An Estimate of India's Uranium Enrichment Capacity." *Science and Global Security* 12: 115–124. doi:10.1080/08929880490464748.
- Ramana, M. V. 2012. *The Power of Promise: Examining Nuclear Energy in India*. New Delhi: Penguin India.
- Ramana, M. V., and A. Kumar. 2010. "Safety First? Kaiga and Other Nuclear Stories." *Economic and Political Weekly* XLV (7): 47–54.
- Ramana, M. V., A. H. Nayyar, and M. Schoeppner. 2016. "Nuclear High-Level Waste Tank Explosions: Potential Causes and Impacts of a Hypothetical Accident at India's Kalpakkam Reprocessing Plant." *Science and Global Security* 24 (3): 174–203. doi:10.1080/08929882.2016.1237661.
- Ramana, M. V., and C. Rammanohar Reddy, eds. 2003. *Prisoners of the Nuclear Dream*. New Delhi: Orient Longman.
- Ramana, M. V., and Z. Mian. 2014. "The Doctrine of the Nuclear Sword." *Himal Southasian*.
- Rehman, I. 2015. *Murky Waters: Naval Nuclear Dynamics in the Indian Ocean*. Washington D.C.: Carnegie Endowment for International Peace. https://carnegieendowment.org/files/murky_waters.pdf
- Reistad, O., and P. L. Ølgaard. 2006. *Inventory and Source Term Evaluation of Russian Nuclear Power Plants for Marine Applications*. Roskilde, Denmark: Nordic nuclear safety research. NKS-139. <http://www.nks.org/scripts/getdocument.php?file=11101011120030>
- Reitzig, A. 2006. "In Defiance of Nuclear Deterrence: Anti-Nuclear New Zealand after Two Decades." *Medicine, Conflict and Survival* 22 (2): 132–144. doi:10.1080/13623690600621112.
- Sagan, S. 1993. *The Limits of Safety: Organizations, Accidents and Nuclear Weapons*. Princeton, NJ: Princeton University Press.
- Sen, S. R. 2012. "Nuclear-Powered Submarine INS Chakra Joins Indian Navy." *NDTV.Com*, April 4. <http://www.ndtv.com/india-news/nuclear-powered-submarine-ins-chakra-joins-indian-navy-474877>

- Sen, S. R. 2014. "India to Lease a Second Nuclear Submarine from Russia." *NDTV.Com*, December 16. <http://www.ndtv.com/india-news/india-to-lease-a-second-nuclear-submarine-from-russia-714039>
- Shukla, A. 2014. "New Naval Base Coming Up Near Visakhapatnam." *Business Standard India*, August 26. https://www.business-standard.com/article/current-affairs/new-naval-base-coming-up-near-visakhapatnam-114082601458_1.html
- Sial, S. A. 2018. "Rationalizing Pakistan's Quest for a Sea-Based Deterrent Force." *Pakistan Politico*, October 18. <http://pakistanpolitico.com/rationalizing-pakistans-quest-for-a-sea-based-deterrent-force/>
- Siddiqui, N. 2019. "Pakistan Navy Foils Attempt by Indian Submarine to Enter Pakistani Waters." *The Dawn*, March 5.
- Singh, A. 2015. "'Blue-Water' Navies in the Indian Ocean Region." *The Diplomat*, January 21. <http://thediplomat.com/2015/01/blue-water-navies-in-the-indian-ocean-region/>
- Sivintsev, Y. V. 2003. "Was the Chazhma Accident a Chernobyl of the Far East?" *Atomic Energy* 94 (6): 421–427. doi:10.1023/A:1025521315143.
- Staff Reporter. 2016. "Turkish Firm to Upgrade Pakistan Submarines." *Dawn*, June 23. <http://www.dawn.com/news/1266665>
- Staff Reporter. 2018. "Pakistan Says Second Strike Capability Attained." *Dawn*, March 30. <https://www.dawn.com/news/1398418>
- Syed, B. S. 2015. "China to Build Four Submarines in Karachi." *Dawn*, October 7. <http://www.dawn.com/news/1211363>
- Takano, M., V. Romanova, H. Yamazawa, Y. Sivintsev, K. Compton, V. Novikov, and F. Parker. 2001. "Reactivity Accident of Nuclear Submarine near Vladivostok." *Journal of Nuclear Science and Technology* 38 (2): 143–157. doi:10.1080/18811248.2001.9715017.
- Thames Television. 1991. "In Deep Water: The Problem with Polaris." <https://www.bfi.org.uk/films-tv-people/4ce2b7b613236>
- Tingle, C. 2009. "Submarine Accidents A 60-Year Statistical Assessment." *Professional Safety*, September.
- TNN. 2014. "INS Arihant Embarks on its First Sea Trials." *The Times of India*, December 16. <http://timesofindia.indiatimes.com/city/visakhapatnam/INS-Arihant-embarks-on-its-first-sea-trials/articleshow/45529440.cms>
- Twomey, C. P. 2011. "Asia's Complex Strategic Environment: Nuclear Multipolarity and Other Dangers." *Asia Policy* 11 (1): 51–78. doi:10.1353/asp.2011.0006.
- Unjhawala, Y. T. 2018. "Deep Diving into the Facts about INS Arihant 'Accident.'" *Economic Times*, January 12. <https://www.economictimes.indiatimes.com/articleshow/62468708.cms>
- Unnithan, S. 2010. "'INS Arihant' to Sail on Deterrent Patrol after Commissioning." *India Today*, December 3. <https://www.indiatoday.in/india/west/story/ins-arihant-to-sail-on-deterrent-patrol-after-commissioning-86461-2010-12-02>
- Unnithan, S. 2017. "A Peek into India's Top Secret and Costliest Defence Project, Nuclear Submarines." *India Today*, December 10. <https://www.indiatoday.in/magazine/the-big-story/story/20171218-india-ballistic-missile-submarine-k-6-submarine-launched-drdo-1102085-2017-12-10>
- Web Staff. 2016. "Pakistan Navy Inducts ATR Aircraft, Unmanned Aerial System in Fleet." *Tele-Visual Infolink* (blog). September 3. <http://tvi.com.pk/pakistan-navy-inducts-atr-aircraft-unmanned-aerial-system-in-fleet/>
- Zee Media Bureau. 2014. "Mishap at Nuclear Submarine Site in Visakhapatnam; One Worker Killed." *Zee News*, March 8. http://zeenews.india.com/news/nation/mishap-at-nuclear-submarine-site-in-visakhapatnam-one-worker-killed_916703.html

**Appendix 1.
Nuclear powered submarine accidents**

Table A1. Accidents with nuclear-powered submarines.

	Name	Kind	Date	Casualties	Nature of accident
United States of America					
1	Thresher	SSN	10.4.1963	129	Sank during deep sea diving
2	Scorpion	SSN	22.5.1968	99	Implosion due to diving below the crush depth
3	Greenville	SSN	9.2.2001	3 crew 4 high school students 2 teachers	Collision with a Japanese Fishing boat while performing an emergency surfacing maneuver
4	Greenville	SSN	28.1.2002	0	Collision with a U.S. naval surface ship
5	Oklahoma City	SSN	13.11.2002	0	Collision with a Norwegian natural gas tanker
6	Hartford	SSN	25.10.2000		Ran aground
7	San Francisco	SSN	8.1.2005	1 died, 23 injured	Collision with undersea mountain
8	Philadelphia	SSN	5.11.2005	0	Collision with a Turkish merchant ship
9	Newport News	SSN	8.1.2007	0	Collision with a Japanese tanker
10	Hartford	SSN	20.3.2009	15 injured	Collision with a transport ship
11	Miami	SSN	23.5.2012	0	Fire
12	Louisiana	SSBN	18.8.2016	0	Collision with a support ship
Soviet Union/Russia					
1	K-8 first accident	SSN	13.10.1960	Crew exposed to radioactivity	Loss of coolant accident (LOCA), leakage of radioactive gases, and contamination
2	K-19 Accident 1	SSBN	4.7.1961	8 immediate deaths plus 14 more from radiation poisoning in next two years	LOCA and spread of fission products
3	K-11	SSN	12.2.1965	7 treated for radiation exposure	Uncontrolled chain reaction, fire
4	K-159	SSN	2.3.1965	0	Leakage of primary coolant into turbines, contaminating the entire propulsion plant
5	K-3	SSN	8.9.1967	39 dead	Fire on board
6	K-27	SSN	24.5.1968	7 died of radiation poisoning	Reactor malfunction and LOCA, and radiation release
7	K-140	SSBN	Aug 1968	?	Control rod malfunction and uncontrolled reactor power surge followed by increased radiation levels

(Continued)



Table A1. (Continued).

	Name	Kind	Date	Casualties	Nature of accident
8	K-8 second accident	SSN	12.4.1970	88 dead	Fire and sinking
9	K-19 Accident 2	SSBN	24.2.1972	30 dead	Fire caused by a breakage in one of the hydraulic pipes
10	K-47	SSN	26.9.1976	8 dead	Fire
11	K-222	SSN	30.9.1980	0	Reactor damaged during maintenance
12	K-123	SSN	8.8.1982	0	Leakage of liquid metal coolant
13	K-429	SSN	23.6.1983	16 dead	Flooding and sinking during test dive
14	K-314	SSN	21.3.1984	0	Collision with US aircraft carrier
15	K-431, originally called K-31	SSN	10.8.1985	10 dead, 49 others exposed to radiation 290 clean-up workers received high radiation doses.	Explosion because control rods were pulled out too fast
16	K-219	SSBN	3.10.1986	4 dead	Explosion and fire
17	K-278	SSN	7.4.1989	42 dead	Fire in electric circuits
18	K-192	SSBN	25.6.1989	Low level radiation exposure of the crew	Leak of primary coolant, LOCA, radioactivity released
19	K-141 Kursk	SSN	12.8.2000	95 dead	Explosion in torpedo compartment
20	K-159	SSN	28.8.2003	9 dead	Sank because of rusting
21	B-414	SSN	6.9.2006	2 dead	Fire on board
22	K-152 Nerpa (subsequently leased to India)		8.11.2008	20 dead +20 others poisoned	Accidental activation of halogen based fire extinguishing system, asphyxiating crew
United Kingdom					
1	Trafalgar	HMS	Nov 2002	0	Ran aground
2	Tireless	HMS	21.3.2007	2 dead	Oxygen generating device explosion under Arctic ice cap
3	Vanguard	HMS	4.2.2009	0	Collision with French naval ship
4	Ambush	HMS	20.7.2016	0	Collision with merchant ship
China					
1	094	SSBN	29.7.2011	?	Radioactivity release
India					
1	Arihant	SSBN	2017	0	Reactor bay flooded through a mistakenly opened hatch
2	Chakra (earlier known as Nerpa)	INS	2017	0	Sonar domes damaged while entering port