India's Stocks of Civil and Military Plutonium and Highly Enriched Uranium, End 2014[1]

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Summary

India has one of the largest nuclear power programs among developing nations. Utilizing plutonium produced in these power reactors and discharged in irradiated or spent fuel, India has developed a relatively large civil plutonium separation program and an associated fast breeder reactor program that is using that separated plutonium.

India has a sizeable nuclear weapons effort. The weapons use separated plutonium produced primarily in a set of small, dedicated reactors and a smaller amount produced in nuclear power reactors. It has a growing gas centrifuge program able to produce significant amounts of highly enriched uranium (HEU) mostly for naval reactor fuel and perhaps for nuclear weapons, including thermonuclear weapons.

India is not transparent about its fissile material stocks. This report estimates India's stocks of separated plutonium and highly enriched uranium. The results are summarized below:

India's HEU and Plutonium Stocks, end 2014			
HEU			
Naval Reactors			
	Cores	HEU (kg)	Range
	4-5 containing HEU	440-880	180-1,800
Thermonuclear Weapons			
	Material	WGU (kg)	Range
	Weapon-grade Uranium (WGU)	150	100-200
Research Reactors			
Apsara	HEU	5 kg	
TOTAL		**440-990**	**280-1,900**
Plutonium			
Military Plutonium (separated)			
	Weapon-grade	Median Value (kg)	Range
		550 kg	375-750
Civil Plutonium in spent fuel			
	Reactor- and fuel-grade	31,900 kg	
Civil Separated Plutonium			
	Fuel- or reactor-grade	**2,900 kg**	

Table 1. India's Fissile Material Stocks as of the end of 2014.

India has a substantial stock of nuclear weapons made from weapon-grade plutonium, and perhaps some thermonuclear weapons that rely on both weapon-grade plutonium and weapon-grade uranium. An estimate of India's nuclear arsenal can be derived by considering its weapon-grade plutonium stock. The resulting estimate has a median of 138 nuclear weapons equivalent with a range of 110 to 175 weapons equivalent. However, the actual number of nuclear weapons India built from its stocks of weapon-grade plutonium must be less. When accounting for the amount of plutonium in the weapons production pipelines and in reserves, it is reasonable to assume that only about 70 percent of the estimated stock of weapon-grade uranium is in nuclear weapons. Thus, the predicted number of weapons made from its weapon-grade plutonium at the end of 2014 is about 97 with a range of 77-123. These values are rounded to 100 nuclear weapons with a range of 75-125 nuclear weapons.

1. India's Civil Plutonium Stockpile

India does not declare its civil inventories of plutonium to the IAEA or to the public. Therefore, this report focuses on estimating them using available information about India's nuclear infrastructure, and specifically its plutonium separation and use activities. However, these estimates remain uncertain because of the shortage of information due to the Indian government's secrecy about many of its nuclear activities related to plutonium separation.

1.1 Civil Plutonium Production

Most of India's operational power reactors are natural uranium fueled heavy water-moderated reactors (PHWRs). India purposely selected these reactors, believing it could make them while bypassing the need to make enriched uranium. At the same time, it wanted reactors that could produce sufficient amounts of plutonium free from international constraints to fuel fast breeder reactors.

At the end of 2014, the Nuclear Power Corporation of India Ltd. (NPCIL) operated 20 nuclear power reactors with an installed capacity of 5,680 MWe. Among these reactors, the 1,000 MWe Kudankulam Nuclear Power Project-1 (KKNPP-1) became operational on December 31, 2014. Its second unit (KKNPP-2) is in advanced stage of commissioning, while the four 700 MWe pressurized heavy water reactors (PHWRs) at Kakrapar, Gujarat and Rawatbhata, Rajasthan were under construction.[2] During the year 2014, India's power reactors recorded an overall capacity factors of about 82 percent. [3] During the year 2014, the availability factor for all the reactors in operation was 89%.[4]

During operation, all of the power reactors produce plutonium in the fuel. As of the end of 2014, Indian power reactors had discharged about 34.8 tonnes of plutonium in spent or irradiated fuel. As will be shown below, several tonnes of this plutonium have been separated and were not in irradiated form at the end of 2014.

[2] Government of India, Department of Atomic Energy, Annual Report, 2014-2015, p. 43, http://dae.nic.in/writereaddata/areport/ar1415.pdf.
[3] Nuclear Power Corporation of India Limited, "Plants Under Operation," 2014, http://www.npcil.nic.in/main/AllProjectOperationDisplay.aspx.
[4] DAE Annual Report, 2014-2015, op.cit.

Unit	Reactor Type	Capacity (MWe)	Commercial Operation (year)	Current Status
Tarapur Atomic Power Station (TAPS), Tarapur, Maharshtra[5]				
1	BWR	160	1969	Operational
2	BWR	160	1969	Operational
3	PHWR	540	2006	Operational
4	PHWR	540	2005	Operational
Rajasthan Atomic Power Station (RAPS) Kota, Rajasthan[6]				
1	PHWR	100	1972	Operational
2	PHWR	200	1980	Operational
3	PHWR	220	2000	Operational
4	PHWR	220	2000	Operational
5	PHWR	220	2009	Operational
6	PHWR	220	2010	Operational
7	PHWR	700	June 2016	Under Construction
8	PHWR	700	December 2016	Under Construction
Madras Atomic Power Station (MAPS), Kalpakkam, Chennai, Tamil Nadu[7]				
1	PHWR	220	1983	Operational
2	PHWR	220	1985	Operational
Narora Atomic Power Station (NAPS), Narora, Bulandshahar, Uttar Pradesh[8]				
1	PHWR	220	1989	Operational
2	PHWR	220	1992	Operational
Kakrapar Atomic Power Project (KAPP) Kakrapar, Surat, Gujarat[9]				
1	PHWR	220	1992	Operational
2	PHWR	220	1995	Operational
3	PHWR	700	Under Review	Under Construction
4	PHWR	700	Under Review	Under Construction
Kaiga Atomic Power Station, Kaiga District, Uttar Kannada, Karnataka				
1	PHWR	220	2000	Operational
2	PHWR	220	1999	Operational
3	PHWR	220	2007	Operational
4	PHWR	220	2011	Operational
Kudankulam Atomic Power Project (KKNP), Tamil Nadu[10]				
1	VVER-PWR	1000	2013	Operational
2	VVER-PWR	1000	December 2015	Under Construction
(3&4)[11]	Expansion of Units 1&2			Planned
Jaitapur Nuclear Power Project, Maharashtra				
(1&2)[12]	EPWR	1650		Planned (in technical cooperation with France)
PFBR in Madras	FBR	500		Under Construction
Gorakhpur Anu Vidyut				
(1&2)[13]		700		Planned

Table 2. India's power reactors.

1.2 Plutonium Separation

India has ambitious plans to separate plutonium to produce MOX fuel for use in fast breeder reactor reactors (FBRs). At present, India has two reprocessing centers in operation at Tarapur and Kalpakkam dedicated to separating plutonium for reuse in civilian reactors. These plants are based on PUREX technology.[14] The one at Kalpakkam has also been used to separate plutonium for military purposes.

India first developed the capability to separate plutonium in 1964, when it commissioned the Trombay reprocessing facility at Bhabba Atomic Research Center (BARC). Its principal purpose is to produce plutonium for nuclear weapons. Trombay has reprocessed irradiated fuel from the relatively small Cirus and Dhruva reactors. It has a nominal capacity of 50-60 tons of spent fuel per year.[15]

The Power Reactor Fuel Reprocessing (PREFRE) facility, located at Tarapur, near Bombay, began operation in 1979. Although designed to separate plutonium from India's PHWRs, it first processed

[5] Tarapur was India's first nuclear power station built as a result of a 1964 contract between India, the United States, and the IAEA. Up to 1974, the United States supplied the fuel for this facility, but then withdrew support after India conducted its first nuclear weapons test. Fuel was subsequently provided by France, China, and Russia under IAEA safeguards. Nuclear Power Corporation of India Limited, *Tarapur Atomic Power Station (TAPS)*, http://www.npcil.nic.in/main/ProjectOperationDisplay.aspx?ReactorID=73.

[6] RAPS was constructed in 1973 with Canadian assistance. However, Canada withdrew its assistance after the 1974 nuclear test. Construction of Units 7-8 were accelerated and are expected to be completed by the end of 2016.See Nuclear Power Corporation of India, http://www.npcil.nic.in/main/ConstructionDetail.aspx?ReactorID=87.

[7] MAPS is the first indigenously built power station. MAPS has experienced several cracks and vibration problems since becoming operational. MAPS also experienced a severe nuclear accident involving the spillage of large amounts of radioactive heavy water, resulting in considerable radiation exposure to seven technicians. Nuclear Threat Initiative, *Madras Atomic Power Station (MAPS)*, 2013, http://www.nti.org/facilities/74/; *Rajasthan Atomic Power Station (RAPS)*, 2014, http://www.npcil.nic.in/main/RAPS_Operating_Experience.aspx.

[8] NAPS has suffered several technical issues including a large fire that ignited after a malfunction in Unit-1. Unit-2 was completely shut down for a month after an air-locking inner door malfunctioned in 1999. On January 9, 2013 NAPS experienced another minor fire. The PHWR reactors at NAPS, RAPS, KAPS, and Kaiga have an added safety feature consisting of a double-domed containment structure. The double dome feature was designed after the Kaiga 1 reactor experienced a partial collapse of its inner dome during construction in 1994. NAPS is not under IAEA safeguards. National Power Corporation of India Limited, *Incident in Turbine Hall of Narora Atomic Power Station Unit-1*, 2013, http://www.npcil.nic.in/pdf/Operating_Experience_narora.pdf.

[9] In November 2010, India started the construction of the first pair of indigenously designed 700 MWe PHWRs. However, the expected date of commercial operation is under review. See *Kakrapar Atomic Power Project*, http://www.npcil.nic.in/main/ConstructionDetail.aspx?ReactorID=91.

[10] The Kudankulam Nuclear Power Project aims at building two new LWRs with a capacity of 1000 MWe each. This project is being implemented with Russian technical cooperation. Although the plants were scheduled for 2007 and 2008, local protests and agitation affected the work between October 2011 and March 2012. Unit-1 was synchronized to the grid in October 2013 and started commercial operation December 2014. Unit-2, is expected to commence operation in December 2015. See *Kudankulam Atomic Power Project*, http://www.npcil.nic.in/main/ConstructionDetail.aspx?ReactorID=77.

[11] The Kudankulam Units 3&4 are an expansion of Units 1&2 and will be implemented in cooperation with Russia. During the year 2013 the project obtained administrative and financial approval and all clearances were obtained. Government of India, Department of Atomic Energy, Annual Reports, 2013-2014, http://www.dae.nic.in/writereaddata/ar2014_v2.pdf.

[12] In October 2009 the Government of India accorded in-principle approval to locate six 1650 MW Evolutionary Pressurized Water Reactors (EPWR) - although only two are planned for now - in technical cooperation with France. The land was acquired from Jaitapur State, environmental and costal clearances were obtained. Pre-project activities are in progress. Government of India, Department of Atomic Energy, Annual Report, 2014-2015, http://dae.nic.in/writereaddata/areport/ar1415.pdf.

[13] The Gorakhpur Anu Vidyut Parlyojana Harayana (GHAVP) aims to build 2 units, each with a capacity of 700 MWe. The land, along with the environmental clearances, were obtained, and the launch of the project is expected in June 2015. Government of India, Department of Atomic Energy, Annual Reports, 2013-2014. http://www.dae.nic.in/writereaddata/ar2014_v2.pdf.

[14] "Indian Programme on Reprocessing," BARC Highlights, http://www.barc.gov.in/publications/eb/golden/nfc/toc/Chapter%206/6.pdf

[15] Ibid.

Cirus's spent fuel.[16] The nominal annual capacity of this facility is usually listed as 100-150 tons of CANDU spent fuel per year, although it rarely ever achieved such capacities.

In 2010, a second plant, PREFRE-II, was commissioned, replacing the first PREFRE facility, now called PREFRE-I. In 2012 and 2013 PREFRE-I was carrying out aged plutonium purification work which typically means removing americium-241 from previously separated plutonium. The americium is a decay product of plutonium-241 and builds up over time in the separated plutonium, increasing the radioactive doses to those who process this older plutonium. PREFRE-II has apparently worked better than PREFRE-I and is achieving high availability factors, which refers to the amount of time the facility is operation, regardless of actual through puts of spent fuel achieved in that time period. The Department of Atomic Energy stated that during 2012-2013 the plant operated with outstanding performance in terms of production and process parameters.[17] There are similar reports in 2014.

India's Kalpakkam Reprocessing Plant (KARP), commissioned in 1998, was also built to process PHWR fuel and has an annual nominal capacity of 100 tons a year.[18] It experienced low irradiated fuel throughputs initially and an accident in 2003 that led to a five year shutdown and renovation. KARP restarted in 2008/2009. This plant has operated more successfully after the renovation. India also initiated a project, named P3A, designed to increase the capacity of PHWR fuel reprocessing at Kalpakkam. A co-located Fast Reactor Fuel Cycle Facility (FRFCF), to reprocess and re-fabricate the fuel from the Prototype Fast Breeder Reactor (PFBR), is being set up at Kalpakkam (see next section). Necessary site infrastructure has already been created.[19]

1.2.1 India's Fast Breeder Reactors

India has an ambitious program to develop fast breeder reactors. It started the small Fast Test Breeder Reactor (FTBR) in 1985 but it has not operated optimally. Nonetheless, it has served to test breeder reactor fuel and components.

India's first 500 MW Prototype Fast Breeder Reactor (PFBR), under construction at Kalpakkam in Tamil Nadu, was scheduled to start operation in 2010.[20] However, this date was later revised. The new date of criticality was first moved to September 2014 with commercial operation envisaged by March 2015.[21] However, in August 2014, the start-up date was further postponed, reportedly well into 2015.[22] As of the date of this report, it has not yet started. The official reasons for the delays appear to be connected to technological complexities of making and quality testing all the

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[16] Government of India, Department of Atomic Energy, Annual Report 1980-81, p.4: Annual Report 1981-81, p.26; Annual Report 1983-84, pp. 6-31; and BARC, Annual Report 1985-86 (BARC: Bombay, 1986).
[17] Government of India, Department of Atomic Energy, Annual Report, 2012-2013, p. 63, http://dae.nic.in/writereaddata/areport/ar1213_big.pdf.
[18] "Indian Programme on Reprocessing" (op. cit.).
[19] Statement by Dr. Ratan Kumar Sinha, International Atomic Energy Agency, 57th General Conference, September 18, 2013, http://dae.nic.in/writereaddata/gc2013_stmt.pdf.
[20] This is a 500 MWe Prototype fast breeder reactor to be built in Kalpakkam and would need about 2 tonnes of plutonium for its initial core and have a refueling requirement of several hundred kilograms of plutonium each year. India's first 40 MWt Fast Breeder Test Reactor attained criticality in 1985 at BARC; the current prototype at Kalpakkam follows a 500 MWe design. Shakti, Anu, *Atomic Energy in India: Fast Breeder Reactors* (date unavailable). Bhabha Atomic Research Centre, Government of India Department of Atomic Energy, http://www.barc.gov.in/about/anushakti_fbr.html.
[21] Shri V. Narayanasamy, Availability of Plutonium for the FBR, Government of India, Department of Atomic Energy, Rajya Sabha Unstarred Question No. 468, August 8, 2013, http://dae.nic.in/writereaddata/parl/mansoon2013/rsus468.pdf.
[22] "Start-up of India's PFBR delayed," *Nuclear Engineering International*, August 11, 2014, http://www.neimagazine.com/news/newsstart-up-of-indias-pfbr-delayed-4340186 .

equipment. Making enough plutonium fuel for the reactor has been challenging because of shortages of separated plutonium due to problems in the plutonium separation plants.[23] Certainly, as will be discussed below, a lack of adequate fuel would have made starting up in 2010 as originally envisioned very difficult.

Indira Gandhi Centre for Atomic Research (IGCAR) Kalpakkam, Tamil Nadu			
Reactor Type	Capacity	Date of Operation	Status
Fast Breeder Test Reactor (FBTR)	40 MWth	October 18, 1985	Operational
Prototype Fast Breeder Reactor (PFBR)	500MWe	Expected 2015/2016	Close to Startup

Table 4. Reactors at the Indira Gandhi Centre for Atomic Research.

India's Atomic Energy Commission intends to follow the PFBR with two more Commercial FBRs whose construction is slated for 2017, although this date could be postponed. Ultimately, the official plan calls for three additional breeder reactors by 2020 before scaling up to 1,000 MWe breeder reactors.

Whether India can build these fast reactors on schedule, including separating enough plutonium for them, is doubtful based on the past performance of its reprocessing plants and breeder program. India's civil reprocessing plants have not worked as planned, raising questions as to whether India can produce enough separated plutonium for such an ambitious fast reactor program.

1.3 Unirradiated Plutonium Inventory

India does not declare its civilian plutonium inventory like those states that submit INFCIRC/549 declarations. It also provides little data allowing a reliable estimate of its stock of unirradiated plutonium, either in separated form, e.g. oxide powders or nitrate solutions, or in MOX fuel, whether for fast or thermal reactors.

There have been many earlier attempts to derive an estimate of India's civilian unirradiated plutonium inventory, including by one of the authors of this report.[24] These estimates have typically tried to estimate throughputs of spent fuel through the PREFRE and KARP reprocessing plants. But without any public data on these throughputs or these plants' capacity factors, these estimates are highly uncertain and unverifiable.

An alternative methodology to derive an estimate of the size of India's current stock of unirradiated plutonium is to consider the production of MOX fuel for India's civil reactors. Because historically India has had a shortage of MOX fuel, almost all civil plutonium separated at its PREFRE and KARP sites is slated for use in MOX fuel and not stored. This method eliminates the need to estimate the actual annual irradiated fuel throughputs in the PREFRE and KARP plants. In

[23] Jaideepa A. Prabhu, "What is India's Plutonium Story?" Centre Right India, January 22, 2013, http://centreright.in/2013/01/what-is-indias-plutonium-story/#.UzsFS6hdU48.
[24] David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996 World Inventories, Capabilities and Policies* (Oxford: Oxford University Press and Stockholm International Peace Research Institute, 1996).

addition, it sidesteps the need to estimate how much of the capacity of KARP has been dedicated to separating plutonium from MAPS fuel for use in nuclear weapons.

India has had several civil reactors that have used plutonium separated at the PREFRE and KARP plants. They are the TAPS reactors, PHWRs, and breeder reactors. Plutonium containing fuels are also being developed for future thorium based reactors, such as the advanced heavy water reactor (AHWR).

The MOX made for the LWRs, PHWRs, and as part of the development of the AHWR has largely been irradiated in the reactors, alleviating the need for precise knowledge about these amounts when determining a current inventory of unirradiated plutonium.[25] In any case, the amount of plutonium assigned to the MOX program for TAPS is relatively small, likely no more than about 50 kilograms.[26] The amount of separated plutonium assigned to the PHWRs and advanced thorium based fuels is likely much smaller than that assigned to the TAPS reactors.

The FBTR has required a larger supply of separated plutonium since the 1980s, when it started. This reactor, however, has never operated at its potential, reducing its plutonium requirements. Thus, its total requirement is estimated below at about 200-300 kilograms of plutonium. Its first core contained initially about 60 kilograms of plutonium and in the 1990s and was slated to receive another 60 kilograms of plutonium to be separated at the PREFRE plant.[27] In 2005, the FBTR was evidently still using its first core, the Mark-1 core. According to the Chairman of the Atomic Energy Commission, as of 2005, the second core, or Mark-2 core, was still awaiting separated plutonium from the KARPs plant, which had been shut down for renovation.[28] The chairman said that separation of plutonium at KARP "for the Mark-2 core is 'on-going.'"[29] Another source states that the Mark-2 core would contain 85.6 kilograms of plutonium 239 and 124.4 kilograms of total plutonium, values consistent with high burnup of spent fuel.[30] The public information supports that these two Mark cores received about 200-250 kilograms of separated plutonium.

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[25] For MOX use in LWRs, see H.S. Kamath, K. Anantharaman, and D.S.C. Purushotham, "MOX Fuel for Indian Nuclear Power Progam," *International Symposium on MOX Fuel Cycle Technologies for Medium and Long Term Deployment: Experience, Advances, and Trends*, May 17-21, 1999. This report lists the irradiation level of eight of the ten fuel assemblies made for the TAPS reactors. A later report, by K.C Sahoo and S.A. Bhardwaj, "Fuel Performance in Water Cooled Nuclear Reactors," INSAC-2003, Kalpakkam, states that ten MOX fuel assemblies had been irradiated in TAPS. The need to further develop MOX fuel for TAPS, which would have required a re-engineering of the TAPS core, was apparently not carried out due to the acquisition of a new contract for low enriched uranium from abroad, according to T.S. Subramanian, "Our Nuclear Power Program is Not Vulnerable, Kakodkar," *The Hindu*, December 7, 2004. The 2003 publication by Sahoo and Bhardwaj states that irradiation of 50 MOX fuel bundles was planned in the one of the PHWR reactors at KAPS. According to H.S Kamath, "Fabrication of Mixed Oxide Fuels for Indian Nuclear Program," INSAC 2003, Kalpakkam. As of 2003, the amount of plutonium in the PHWR fuel bundles was relatively small, where of the 19 elements of a fuel bundle only seven elements contained plutonium and the plutonium oxide content of these element was 0.4 percent. The other 12 elements contained natural uranium oxide. Subsequently, 50 MOX bundles were loaded into a PHWR at Kakrapar, according to Srikumar Banerjee, Diretor of BARC, *Founder's Day Address,* October 28, 2005. India had plans many years ago to make more MOX assemblies for the TAPS reactors, although it is unclear from public information whether India did so. In any case, this requirement is seen as relatively small compared to the need for plutonium for the PFBR and also much less of a priority. The latter argues that little plutonium was assigned to the TAPS reactors or PHWRs.

[26] R. Chidambaram and C. Ganguly, "Plutonium and Thorium in the Indian Nuclear Program," *Current Science*, vol. 70, no. 1, January 10, 1996. Each MOX fuel assembly contained 3.4 kilograms, see figure 8, p. 30. Thus, ten fuel assemblies would have a mass of 34 kilograms.

[27] Mark Hibbs, "First Separation Line at Kalpakkam Slated to Begin Operations Next Year," *Nuclear Fuel*, December 1, 1997.

[28] Mark Hibbs, "DAE Reprocessing Program Remains Modest in Scope," *Nuclear Fuel*, April 14, 2003.

[29] Ibid.

[30] International Atomic Energy Agency, Fast Reactor Database, 2006 Update, IAEA-TECDOC-1531, December 2006, p, 32, http://www-pub.iaea.org/MTCD/Publications/PDF/te_1531_web.pdf.

The main requirement for separated plutonium has been the PFBR. In 2004, Anil Kakodkar, Chairman of the AEC, said that India had plans to use the MOX fuel for breeder reactors, implying that large-scale MOX fuel use in the TAPS or PHWR reactors was not preferred.[31]

With the PREFRE and KARP reprocessing plants not working well in the 1990s and 2000s, India developed a plutonium shortage for the PFBR. That there was a shortage of separated plutonium for this reactor can be witnessed by official statements:

- During the 2007 Founder's Day Address, the Director of BARC stated the current priorities, of which the "first and foremost is to meet our commitment to supply fuel for the PFBR. As you are aware, this is a very big task, which involves reprocessing large quantity of spent fuel and converting the recovered plutonium into fast reactor fuel of exacting specifications."[32] He added that they "have been working against time to meet this immediate requirement."
- In 2008, the Director of BARC stated, "With KARP coming back to operation, we will be able to accelerate the production rate of fast reactor fuel, which I consider the most important mandate of BARC in the immediate future."[33]
- In 2009, the Director of BARC stated, "Today, a bigger challenge lies ahead of us to supply the mixed oxide fuel requirements for the Prototype Fast Breeder Reactor."[34]

The vast bulk of any civil plutonium separated has gone into the fuel of the PFBR. Since this reactor has not yet operated, the fuel contains fresh plutonium. Unirradiated plutonium outside this fuel and associated fuel manufacturing complex is likely relatively small.

Media reports state that the initial core of the PFBR would need 1.9-2.0 tonnes of plutonium for its initial criticality.[35] A technical study from 1999 contains data that allows a more rigorous estimate of the core's plutonium content, although missing data leads to a broader range, namely 1.7-2.3 tonnes.[36] Here, the average of 2 tonnes is used in subsequent estimates.

The PFBR will require refueling and thus additional plutonium. A 2003 estimate stated that the PFBR would need about 400 kilograms of plutonium annually, if it operates relatively well.[37]

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[31] T.S. Subramanian, "Our Nuclear Power Program is Not Vulnerable, Kakodkar" *The Hindu*, December 7, 2004.
[32] Srikumar Banerjee, Director BARC, *Founder's Day Address 2007*, http://www.barc.gov.in/presentations/fddir07.html.
[33] Srikumar Banerjee, Director BARC, *Founder's Day Address 2008,* http://www.barc.gov.in/presentations/fddir08.html.
[34] Srikumar Banerjee, Director BARC, *Founder's Day Address 2009,* http://www.barc.gov.in/presentations/fddir09.pdf.
[35] "DAE Reprocessing Program Remains Modest in Scope," op. cit. and "First Separation Line at Kalpakkam Slated to Begin Operations Next Year," (op. cit.).
[36] "MOX Fuel for Indian Nuclear Power Progam," *International Symposium on MOX Fuel Cycle Technologies*, op. cit. Table IV provides a linear mass density of each MOX fuel pin of about 2.33 grams per centimeter. Another study, "Design of Prototype Fast Breeder Reactor," by Indira Gandhi Centre for Atomic Research (December 2003), states that each fuel pin has a central section of 100 centimeters of annular MOX fuel. In total, each fuel pin would contain 233 grams of MOX material, namely plutonium and uranium oxides. With 217 pins per assembly and a total of 181 assemblies, the core would contain 9,151 kilograms of MOX material, close to the 9.2 tonnes given in Table IV. Here, the total refers to the combined mass of the uranium oxide and plutonium oxide in the fuel. Considering only the mass of the uranium and plutonium reduces the total to about 8,053 kilograms of uranium and plutonium. The fraction of plutonium in the fuel varies, an unspecified amount of the MOX fuel is enriched to 21 percent plutonium oxide and another amount is enriched to 28.4 percent plutonium oxide. First considering the extremes, where all MOX fuel is either enriched to 21 percent or 28.4 percent range, the total amount of plutonium is 1.7 tonnes or 2.3 tonnes, respectively. The average is 2 tonnes of plutonium.
[37] S. Govindarajan, "Economics of FBR Fuel Cycle," INSAC 2003, Kalpakkam.

One estimate of the amount of civil irradiated plutonium put into PFBR fuel is based on an assessment of public statements about progress in making this reactor's fuel.

- In 2007, manufacturing of MOX fuel pins for the PFBR started at the Tarapur MOX fabrication plant and 434 pins were made.[38] Each fuel assembly contains 217 pins, meaning that two fuel assemblies were made in that year, out of a total of 181 needed. These assemblies contained about 22 kilograms of plutonium, based on assuming that the initial core contains about 2 tonnes (2,000 kilograms) of plutonium.
- In 2009, the landmark of 1,000 PFBR fuel pins was achieved at the Tarapur MOX plant.[39] 1,000 fuel pins contained about 51 kilograms of plutonium.
- After a five year renovation, KARP went back on-line in 2008 and 2009. The rate of separation of plutonium likely increased significantly afterwards.[40] PREFRE II started processing radioactive material in early 2011, contributing to greater plutonium separation.
- In 2013, the Advanced Fuel Fabrication Facility at Tarapur was working continuously and had fabricated 75 percent of the fuel needed for PFBR's criticality, corresponding to 1,500 kilograms of unirradiated plutonium.[41]
- By early January 2014, 95 percent of fuel required for PFBR criticality had been fabricated, corresponding to 1,900 kilograms of unirradiated plutonium.[42]
- By the end of the 2014, 100 percent of the fuel needed for criticality had been made.[43]

Given that almost all separated plutonium has gone into making PFBR fuel, and much of the rest is already irradiated in reactors, India's civil unirradiated plutonium inventory as of the end of 2013 is taken as about 1.9 tonnes in FBTR fuel and another several hundred kilograms in unirradiated form at the PFBR fuel manufacturing complex, a stock of aged plutonium slated for processing at PREFRE-I, a stock of plutonium freshly separated at KARP and PREFRE-II, and miscellaneous amounts. These additional stocks probably do not exceed several hundred kilograms. In sum, India's civil plutonium inventory at the end of 2013 is estimated to be 2,500 kilograms. Most of this plutonium will become irradiated once the PFBR starts, lowering the inventory of unirradiated plutonium.

A crude estimate of the current rate of plutonium separation can be drawn from the above data on the fabrication of PFBR fuel. Up to 2009, when the renovated KARP started and before PREFRE-II started, little plutonium was separated. From 2009 to sometime in 2013, about 1.5 tonnes were fabricated into fuel, or about an average of about 370 kilograms of plutonium per year. From 2013 through early 2014, about 400 kilograms were fabricated into fuel. These amounts correspond to the annual average separation of plutonium at the PREFRE-II and KARP plants. Thus, India is separating far more plutonium today than it did ten years ago, prior to KARP's renovation and the start of PREFRE-II.

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[38] Srikumar Banerjee, Director BARC, *Founder's Day Address 2007,* http://www.barc.gov.in/presentations/fddir07.html.
[39] Srikumar Banerjee, Director BARC, *Founder's Day Address 2009,* http://www.barc.gov.in/presentations/fddir09.pdf.
[40] Srikumar Banerjee, Director BARC, *Founder's Day Address 2009,* http://www.barc.gov.in/presentations/fddir09.pdf.
[41] Sekhar Basu, Director BARC, *Founder's Day Address 2013,* http://www.barc.gov.in/presentations/fddir13.pdf.
[42] 65th Republic Day Speech by Director, BARC, January 26 2014, http://www.barc.gov.in/presentations/20140126.pdf.
[43] Sekhar Basu, Director BARC, *Founder's Day Address 2014,* October 30, 2014, http://gcnep.gov.in/presentations/fddir14.pdf.

These values can be used to estimate that India separated another 400 kilograms of plutonium in 2014. Thus, India's estimated stock of separated plutonium is about 2,900 kilograms at the end of 2014.

The annual rate of separated plutonium can be converted into a corresponding rate of unirradiated fuel processed at the reprocessing plants. A reasonable estimate is that the irradiated fuel contains about 3.5 kilograms of plutonium per tonne of fuel. At this concentration, an annual average separation of 400 kilograms of plutonium would correspond to about 115 tonnes of irradiated fuel per year.

2. India's Military Plutonium Stockpile

Despite many obstacles, India has managed over several decades to put in place a relatively large nuclear weapons production complex. Its current complex can produce plutonium and highly enriched uranium for nuclear weapons and nuclear powered submarines. It has a sophisticated missile production complex that provides the delivery systems for its nuclear weapons.

Indian nuclear weapons use weapon-grade plutonium. The bulk of this plutonium for nuclear weapons has come from the Cirus and Dhruva heavy water reactors, both located at the Bhabba Atomic Research Center (BARC) in Mumbai. Canada supplied the Cirus reactor for peaceful purposes only, and India designed and built the Dhruva reactor. India likely procured many goods for these reactors overseas.

The plutonium from these reactors has been separated from the irradiated fuel at the adjacent Trombay plant. India started the Trombay plutonium separation plant in 1964 to reprocess irradiated fuel from the Cirus reactor. It was shut down in 1974 for renovation and expansion and restarted in 1983 or 1984. While the Trombay plant was closed, Cirus' irradiated fuel was processed at the nominally civil PREFRE reprocessing plant north of Mumbai that began operation in 1979. Afterwards, the Trombay plant processed the irradiated fuel from both the Cirus and Dhruva reactors.

According to a senior U.S. official, after the 1998 tests, India used its civil power reactors to "surge" weapon-grade plutonium production for its nuclear weapons program. India explained to U.S. officials at that time that it needed to build up its weapons plutonium stock after the 1998 tests before it engaged in negotiations for a Fissile Materials Cutoff Treaty (FMCT), negotiations which have still not come to fruition. It may have subsequently produced additional weapon-grade plutonium for nuclear weapons in its civil power reactors. In addition, during power reactor startup, the first fuel discharges usually contain weapon-grade plutonium, which may have been processed for weapons use.

India may have also held a stock of reactor-grade plutonium potentially for use in nuclear weapons. Although generally India is not believed to use reactor-grade plutonium in nuclear weapons, Indian nuclear experts are reported to have evaluated this plutonium's use in nuclear weapons and India may have decided to create a reserve stock of reactor-grade plutonium for possible use in nuclear weapons.

2.1 Dhruva Reactor

The 100 megawatt-thermal (MWth) Dhruva reactor went critical in August 1985 and continues operating today. Soon after starting operation, the reactor experienced severe vibrations in the reactor core and was shut down for modifications. In December 1986, it resumed operation at quarter power, or 25 MWth. In January 1988, the vibration problem was solved and the reactor attained nominal powers. Its operation since then has been consistent, albeit it has never operated consistently at its potential.

Estimating the total energy output of the Dhruva reactor is complicated because India has typically released publicly information only about the availability factor of this reactor. The availability factor is defined as the amount of time that a reactor is able to produce power over a certain period, regardless of its actual power, divided by the amount of the time in the period. However, this term does not allow one to estimate plutonium production, since the capacity factor (total energy output of the reactor in this period) is not given. The capacity factor is necessary because it allows the derivation of the total amount of energy produced by the reactor during a period of time divided by the amount of energy the plant would have produced at full power, e.g. 100 MWth for the Dhruva reactor. The capacity factor for a period will always be less than the equivalent availability factor for the same period, where the difference depends on the actual utilization of the power plant.

For the Dhruva reactor, official publications routinely list the annual or monthly availability factors as 70 or 80 percent.[44] However, its capacity factors are much lower. In the 68th Independence Day Address, 2014, the Director of BARC said that Dhruva "continued to operate at an enhanced power level of up to 80 MW, with availability factor of about 81% and **highest ever capacity factor of about 53%** (emphasis added)."[45] This rare admission indicates that annual capacity factors were much less than availability factors and in fact it is likely that they were significantly less than 53 percent. The calculation assumes that the capacity factor is a triangular distribution with an upper bound of 0.53, a lower bound of 0.3, and a peak of 0.4.

Such an interpretation is supported by widely circulated statements by U.S. government experts in the late 1990s. These knowledgeable experts from U.S. national laboratories stated in briefings that the Cirus and Dhruva reactors had by the late 1990s achieved a lifetime capacity factor of only about 40 percent.

2.2 Cirus Reactor

The 40 megawatt-thermal (MWth) Cirus reactor, supplied by Canada, first went critical in 1960. It operated until 2010.

The reactor experienced start-up issues that delayed the reactor reaching nominal powers until 1963. This reactor operated until 1997 when it shut down for major renovations because of aging problems. India had considered building a new reactor to replace Cirus, but decided against that option for cost reasons. After extensive modification, the reactor restarted in October 2003. It achieved full power of 40 MWth in November 2004 with an average availability factor of about 70

[44] See various *Founder's Day Addresses* by the Directors of BARC.
[45] *68th Independence Day Address by Director, BARC,* 2014, http://www.barc.gov.in/presentations/20140815.pdf.

percent. In December 2004, the reactor achieved its highest ever availability factor of 94.78% and a capacity factor of 90.82% for the month.[46]

Despite reaching a capacity factor of 91 percent for one month in December 2004, the reactor is believed to have a lifetime capacity factor far below this value and its publicly provided availability factors, which remained relatively high. For example:

- Cirus operated generally at 20 MWth with the availability factor of 90.2%.[47] However, reactor power was raised to higher levels as and when required. Because the power was half that of its maximum power of 40 MWth, the capacity factor was less than 50 percent.
- Cirus had availability around 80 percent.[48]

The lifetime capacity factor, however, is believed to be relatively low. How much lower is hard to determine, particularly in the years following its refurbishment. In this estimate, Cirus' lifetime capacity factor is assumed to be somewhere between 30 and 50 percent.

After the Cirus reactor was refurbished in the early 2000s, Indian officials expected it to last for about 15 more years. However, one accomplishment of the U.S./India nuclear cooperation agreement is that India agreed to shut down the Cirus reactor, despite its recent renovation. Its early shutdown was part of an arrangement where India agreed to provide a clearer separation between its civil and military nuclear programs. This reactor was provided by Canada under an agreement that it would be used for peaceful purposes. The arrangement, however, did not ban the use of Cirus' plutonium in nuclear weapons. India's signing of the agreement prevented the continued use of the Cirus reactor to make additional plutonium for nuclear weapons.

The reactor was shut down for the last time on December 31, 2010 and its irradiated fuel removed for subsequent reprocessing and plutonium recovery.[49] In the end, Cirus is estimated to have operated for a total of about 39-41 years.[50]

2.3 PHWR Reactors

Through 2014, India has put into operation a total of 16 unsafeguarded pressurized heavy water power reactors (PHWRs) (see section on civil plutonium). Because it is unknown if all the initial fuel from the PHWRs were assigned to the military program, this contribution to the total military stock remains uncertain. An upper bound is 80 kilograms of weapon-grade plutonium, but the actual amount could be less; here the minimum is taken as about 30 kilograms.

India is believed to have drawn military plutonium from its PHWRs in two ways. First, it reportedly recovers weapon-grade plutonium from the first irradiated fuel discharges from its

[46] Srikumar Banerjee, Director of BARC, *Founder's Day Address*, October 28, 2005, http://www.barc.gov.in/presentations/dirsp2005.html.
[47] Dr. Srikumar Banerjee, Director, BARC, *59th Republic Day of India*, January 26, 2008, http://www.barc.gov.in/press/2008/01.html.
[48] Srikumar Banerjee, Director BARC, *Founder's Day Address 2009,* October 30, 2009, http://www.barc.gov.in/presentations/fddir09.pdf.
[49] R.K. Sinha, Director, BARC, *Founder's Day Address*, October 28, 2011, http://www.barc.gov.in/presentations/fddir11.pdf.
[50] The years of operation are roughly 1963-1997 and 2004-2010.

PHWRs and assigns this plutonium to the military program.[51] Each reactor could discharge during start-up low burnup fuel containing about 5 kilograms of weapon-grade plutonium.[52]

India has also used its PHWRs in a more dedicated manner to make plutonium for its military program. As discussed above, at least one case of such production occurred in the late 1990s. It is unknown if there were other campaigns at a later date. A limiting factor is that its reprocessing plants able to separate plutonium from PHWR spent fuel have not worked well. Thus, a dedicated campaign may have produced only tens of kilograms of weapon-grade plutonium. In this estimate, it is assumed that the surge in the late 1990s produced 20-40 kilograms of weapon-grade plutonium. There is no concrete information suggesting subsequent dedicated campaigns, but such campaigns could have occurred and represent an uncertainty in this overall plutonium estimate.

2.4 Total Production of Plutonium, all sources

Any estimate of India's weapon-grade plutonium inventory remains highly uncertain. Complicating any estimate is the mixture of solid and ambiguous information regarding India's capabilities and actions. As a result, an analytical approach is used that specifically aims to capture varying and conflicting information about key parameters affecting estimates of the size of India's plutonium stock. Rather than deciding on a best estimate for a specific parameter, such as lifetime reactor operating capacity factor, a frequency distribution of possible parameter values is derived.

Using Crystal Ball® software, distributions representing key parameters in a formula are sampled using a Monte Carlo approach to derive a distribution of results. This method varies from an earlier approach used one of the authors, where central or best estimates were derived, and an uncertainty was attached by making a judgment about the overall data and information.[53] Although judgments are still necessary in any uncertainty analysis, they can be applied in a more transparent manner with this software.

The formula used to estimate the total amount of weapon-grade plutonium produced in the Cirus or Dhruva reactors is straightforward:

Total Plutonium (kgs) = P (Reactor Power) x C (Capacity Factor) x D (Days in Operation)
x PF (Plutonium Conversion Factor) x 0.001

where the plutonium conversion factor (PF) serves to convert the amount of energy produced by the reactor into the amount of weapon-grade plutonium in the discharged fuel, in units of grams of weapon-grade plutonium per energy produced g/MWth-d. For the production of weapon-grade plutonium, values of 0,8-0.9 g/MWth-d are used for the Cirus and Dhruva reactors, reflecting uncertainties in the design and operation of these reactors.

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[51] Mark Hibbs, "Indian PHWR Safeguards Offer Not Impressive, NPT States Say," *Platts Nucleonics Week*, April 17, 2003; see also *Plutonium and Highly Enriched Uranium 1996*, op. cit., p. 266-7.
[52] *Plutonium and Highly Enriched Uranium 1996*, op. cit., p. 267.
[53] See for example *Plutonium and Highly Enriched Uranium 1996*, (op. cit.).

A more rigorous plutonium production calculation could result in a more accurate estimate, particularly of the plutonium conversion factor. However, India does not make publicly available detailed technical information about these reactors and their operation.

In addition to the weapon-grade plutonium produced in the Cirus and Dhruva reactors, the calculation also includes estimates of weapon-grade plutonium produced in India's power reactors. Figure 1 shows the estimate of total weapon-grade plutonium production from all sources. The median is about 660 kilograms. The full range is 485 to 850 kilograms.

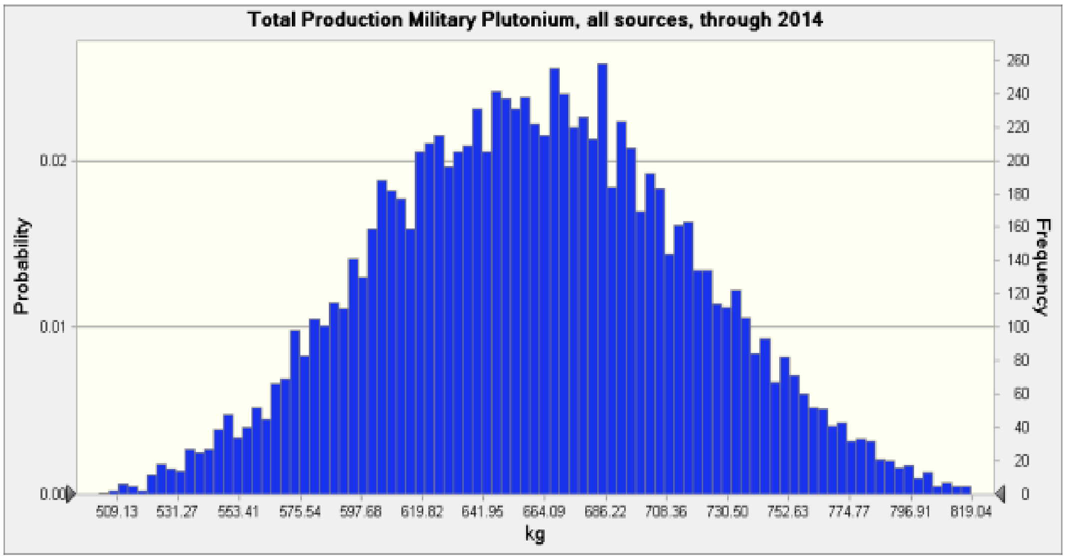

Figure 1. Total Plutonium Production, all sources

2.5 Draw Downs

Some of Cirus' and Dhruva's plutonium has been used in nuclear tests, lost in processing, or assigned to civil fuel. These quantities must be subtracted to derive the net weapon-grade plutonium stock. The civil reactors utilizing plutonium from the Cirus or Dhruva reactors include the Fast Breeder Test reactor (FBTR), the Purnima reactor, and possibly some of the plutonium used in power reactor fuel. Nuclear testing in 1974 and 1998 also used a portion of this plutonium. As above, many of these drawdowns had to be estimated and are approximated by ranges in the Crystal Ball® calculation.

- The FBTR is estimated to have used 30-50 kilograms of plutonium produced in the Cirus reactor;
- The Purnima reactor used about 19 kilograms; the material was recovered but it is assumed that it was not used in nuclear weapons. Additional plutonium, up to ten kilograms from the Cirus reactor, could have been assigned to MOX fuel for LWRs;
- Nuclear testing in 1974 consumed somewhere between five and seven kilograms;
- Nuclear testing in 1998 consumed between 20 and 30 kilograms of plutonium; and
- Process losses during reprocessing are assumed to be two to four percent of total plutonium produced.

The total estimated amount of drawdowns has a median of about 110 kilograms and lower and upper bounds of 87 and 131 kilograms, respectively (see figure 2).

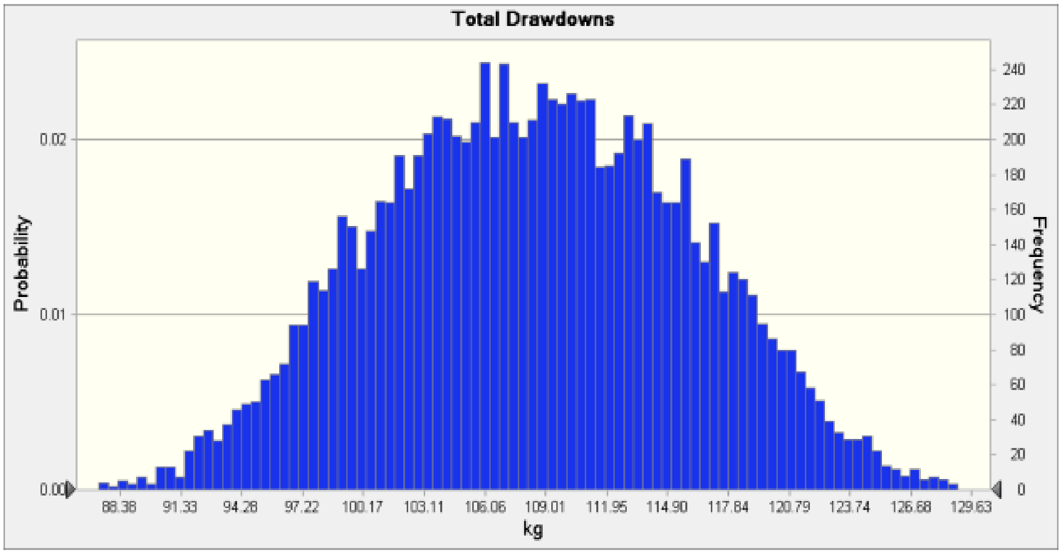

Figure 2: Plutonium Drawdowns.

2.6 Net Plutonium Inventory, End of 2014

The net military inventory is calculated with Crystal Ball® software by evaluating the total amount of military plutonium produced minus the amount of plutonium used in nuclear testing, lost during processing, and assigned to civil uses. At the end of 2014, the median value of the estimate of this net inventory is about 550 kilograms of plutonium, and the lower and upper bounds are 375 and 750 kilograms, respectively.

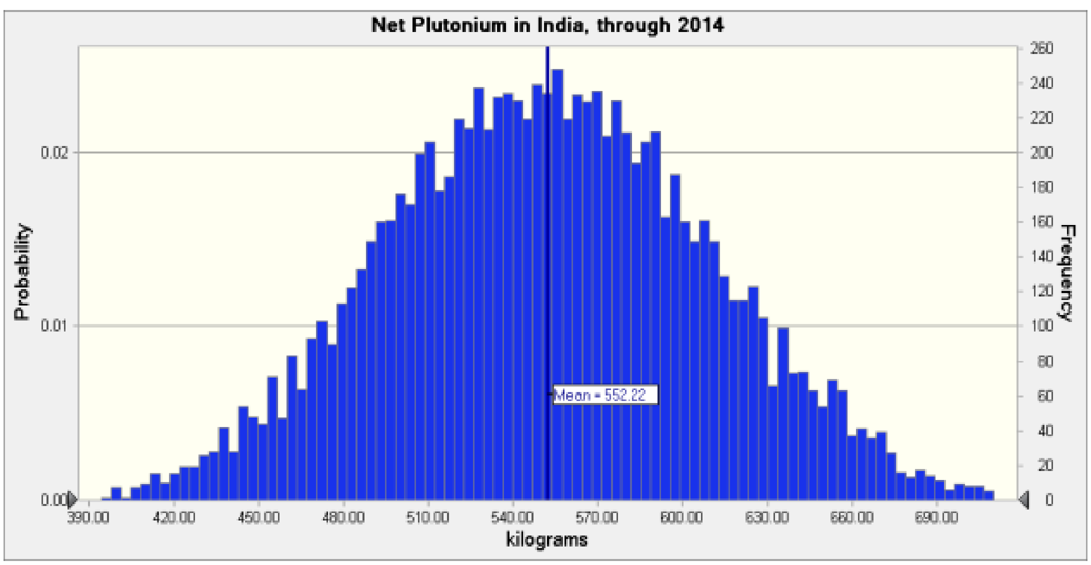

Figure 3: Net Plutonium Inventory, end of 2014.

2.7 Estimated Number of Nuclear Weapons, End of 2014

India has extensive expertise about making nuclear weapons from plutonium, including knowledge and experience gained in its 1974 and 1998 underground nuclear tests. India's weapons likely use weapon-grade plutonium, and it is believed to have multiple fission weapon designs suitable for different types of delivery systems.

In this study, an Indian plutonium-based weapon is assumed to contain between three and five kilograms of weapon-grade plutonium. Although five kilograms are rather large, this figure is viewed as an upper bound. A weapon could use this amount of plutonium in order to increase its explosive yield or permit further miniaturization. Similarly, three kilograms may be low but should be within India's capabilities. With little information about modern Indian nuclear weapons, all values in the range are viewed as equally likely.

The resulting calculation using Crystal Ball™ software results in a skewed distribution with a median of about 138 nuclear weapons equivalent. The distribution's standard deviation is about 25 weapons equivalent and the full range is about 80 to 230 weapons equivalent, where the upper bound reflects the skewness of the distribution. Over 80 percent of the values are in the range of 110-175, which is the range used for this estimate.

The actual number of nuclear weapons India built from its stocks of weapon-grade plutonium is unknown. With requirements for plutonium in the weapons production pipelines and in reserves, it is reasonable to assume that only about 70 percent of the estimated stock of weapon-grade uranium is in nuclear weapons. Thus, the predicted number of weapons made from its weapon-grade plutonium at the end of 2014 is about 97 with a range of 77-123. These values are rounded to 100 nuclear weapons with a range of 75-125 nuclear weapons.

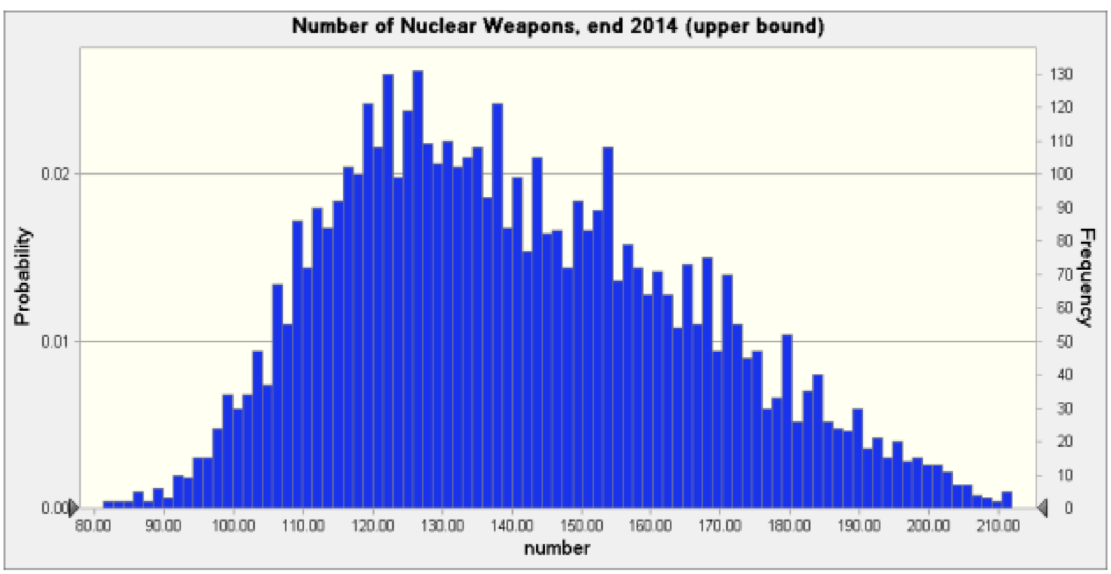

Figure 4: Number of Nuclear Weapons Equivalents.

3. India's Highly Enriched Uranium Stockpile

Great secrecy surrounds India's gas centrifuge enrichment program, the country's source for highly enriched uranium (HEU). The program started in the 1970s, but progressed slowly compared to Pakistan's centrifuge program, which rapidly expanded in the 1980s and 1990s. However, after many years, India has developed the capability to build and operate centrifuge plants. During the last decade, it has expanded its gas centrifuge program and its ability to make highly enriched uranium for its military nuclear programs.

Although the history and current status of India's gas centrifuge program is secret, an assessment of this program, and in particular an estimate of its production of HEU, is possible through open source information, procurement data, statements made by Indian officials, and satellite imagery.

The Indian government designated its gas centrifuge enrichment facilities as military sites under the framework of a U.S./India nuclear cooperation agreement. India uses highly enriched uranium from these plants in submarine reactor fuel and likely nuclear weapons.

Although the centrifuge program has developed with the support of domestic suppliers, it has depended extensively on foreign suppliers for several key items. The extent of its dependence on foreign supplies is not known well enough to know if export controls and sanctions have delayed India's centrifuge program. There are also no indications that the Indian centrifuge program has stopped illicitly procuring some goods from abroad.

3.1 Early Centrifuge Program

India's first centrifuge facility was at the Bhabha Atomic Research Center (BARC) at Mumbai. By 1986, this facility was reported to contain about 100 centrifuges operating in a cascade and to have enriched uranium up to about two percent uranium 235.[54] Centrifuge research and development activities have continued at BARC.

The Indian centrifuge and likely associated cascade designs appear based on European, or URENCO, centrifuge designs. Design information about these centrifuges was available both publicly and from some of the employees of India's Western suppliers who had access to this information as a result of contacts with URENCO subcontractors and their dealings with the Pakistani nuclear black market ring led by A.Q. Khan and his colleagues.[55] Although surprising that URENCO subcontractors would sell to bitter rivals India and Pakistan, the reality was that these suppliers prioritized profit and were well known as sellers of reliable high-tech equipment sought by a variety of customers, particularly centrifuge programs. However, India did not appear to obtain a complete centrifuge design as had Pakistan and Iran in the 1970s and 1980s. The latter period is when these suppliers were selling a range of goods to India's centrifuge program.

In an interview with one of the authors in March 1992, P. K. Iyengar, then Chairman of the Atomic Energy Commission (AEC), stated that the early centrifuges did not have bellows, implying that he was aware of the European designs that are known to rely on bellows. The bellows is a sensitive

[54] Ivan Fera and Kannan Srinivasan, "Keeping the Nuclear Option Open, What it Really Means," *Economic and Political Weekly*, vol. 21, no. 49, December 6, 1986.
[55] David Albright and Susan Basu, *India's Gas Centrifuge Enrichment Program: Growing Capacity for Military Purposes*, Institute for Science and International Security, January 18, 2007; and Albright, *Peddling Peril* (New York: Free Press, 2010).

item used in longer centrifuge rotors to allow the centrifuge to pass through certain critical resonant frequencies safely as the rotor speeds up to its operational speed. In general, the longer the rotor, the greater is its enrichment output, so programs are motivated to find ways to overcome these resonances and the bellows is the solution developed by URENCO to allow longer centrifuges. In contrast, the U.S. and former South African centrifuge programs handled the resonance problem differently and did not require bellows. For the type of centrifuges that use bellows in order to reach longer rotor lengths, the ones with bellows are considered more advanced than those that do not have any.

The rotor materials also matter, since stronger, lighter materials allow for faster rotor speeds and thus higher enrichment outputs. Early in the program, namely during the 1970s and early 1980s, India's rotors were likely made from high-strength aluminum rather than maraging steel. Without bellows, the enrichment output of an aluminum-rotor centrifuge was likely in the range of 0.5-1.0 kg U swu/year. These centrifuges should probably be viewed as India's first generation centrifuges.

3.2 Rare Materials Plant (RMP)

In 1982, the Indian Department of Atomic Energy decided to "construct a classified technology demonstration project," the Rare Materials Project (RMP) near Mysore as a unit of the Bhabha Atomic Research Center (BARC) for the purpose of enriching uranium.[56] The main uses of the enriched uranium have been to fuel nuclear powered submarines. Because India is widely believed to have worked on thermonuclear weapons since the 1980s or 1990s and such weapons typically require highly enriched uranium, the RMP is also suspected to have produced HEU for nuclear weapons.[57] In addition, the RMP may have provided or will provide enriched uranium for use in civil research reactors. However, little, if any, HEU has been produced for civil research reactors as of the end of 2014.

Although the status of this project has been secret, ISIS used publicly available procurement data in the mid-2000s to find the location of the Mysore plant[58] and high resolution commercial satellite imagery has allowed on-going monitoring of the developments at this site (see below).

The original Department of Atomic Energy (DAE) goal was reportedly to have about 5,000 operating centrifuges at the RMP.[59] This number, however, was likely a long term goal and should be viewed as the number intended for installation in the initial centrifuge building at the RMP, not the number installed initially.

Despite the purchase of a large amount of equipment from abroad, India encountered serious technical difficulties in building and deploying centrifuges. Up until the 2000s, the plant experienced frequent breakdowns and many centrifuges are believed to have failed.[60]

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[56] Statement of objections filed by the Respondent Nos. 10 (Bhabha Atomic Research Centre) and 12 (Defense Research and Development Organization, Before the National Green Tribunal (SZ) Chennai, Appl. No. 6 2013.

[57] See for example, Albright and Tom Zamora (Collina), "India, Pakistan's Nuclear Weapons: All the Pieces in Place," *Bulletin of the Atomic Scientists*, June 1989, pp 20-26.

[58] *India's Gas Centrifuge Enrichment Program: Growing Capacity for Military Purposes*, op. cit. See in particular footnote 57.

[59] "Keeping the Nuclear Option Open," op. cit. This source states that the RMP will be scaled up fifty times from the pilot plant at BARC.

[60] *Plutonium and Highly Enriched Uranium 1996,* op. cit., pp. 269-271; and *India's Gas Centrifuge Enrichment Program: Growing Capacity for Military Purposes*, op. cit.

RMP's history up to the mid-2000s is traced in an ISIS technical report and is not repeated here.[61] At the end of this period, based on centrifuge drawings in RMP tender documents, India's centrifuges were achieving single machine enrichment outputs estimated to be about 5-7 swu/year.[62] This assessment of their single machine enrichment output was conducted by two groups of centrifuge experts who evaluated the design drawings of rotors and bellows in these tender documents. They also pointed out that the designs were not exact URENCO centrifuge designs and in fact had some design weaknesses which would have interfered in their reliability and operation. Nonetheless, a rough estimate of RMP total theoretical enrichment capacity in 2005 was earlier estimated by one of the authors as about 4,000-15,000 swu/year.[63]

Over the last decade, the centrifuge project has further matured and allegedly proved itself at the demonstration scale. This was demonstrated by several actions to substantially increase enrichment capacity.

In 2006, India commissioned a new cascade hall, presumably in the original building at RMP. According to the Director of BARC, "Successful installation and commissioning of the new cascade hall of high speed machines has augmented production capacity of enriched uranium."[64]

This new cascade hall may have been outfitted with centrifuges ordered in 2005 and early 2006 of the same type ordered in the tender documents mentioned above.[65] The total order involved about 3,000-4,000 centrifuges of two related types, where the two types had outputs of about 5 and 7 swu/year.[66] With the installation of the newer centrifuges, a process that likely took at least a few years, the RMP's capacity would have significantly increased.

By about 2010, it is likely that many of these newer centrifuges would have been installed in the RMP and many older models retired. In total, RMP's theoretical enrichment capacity in 2010 is estimated to have been approximately 15,000-25,000 swu per year, assuming a mix of old and new machines.[67] The actual achieved enrichment output with the centrifuges operating in cascades would likely have been less due to inefficiencies encountered in large-scale operation.

To put this enrichment capacity in context, if all of it were used to make weapon-grade uranium, this capacity is enough to make about 60-100 kilograms of WGU per year.[68] Another method to understand this capacity is to consider the amount of enriched uranium needed for a naval reactor core. As derived below, this capacity would be sufficient to make about one or two cores per year.[69] However, it should be emphasized that the actual enrichment output may have been far smaller.

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[61] *India's Gas Centrifuge Enrichment Program: Growing Capacity for Military Purposes*, op cit.
[62] Ibid.
[63] Ibid.
[64] Dr. Srikumar Banerjee, Director, BARC, *Founder's Day Address 2006*, October 30, 2006. http://www.barc.gov.in/presentations/fddir06.html
[65] *India's Gas Centrifuge Enrichment Program: Growing Capacity for Military Purposes*, op cit.
[66] *India's Gas Centrifuge Enrichment Program: Growing Capacity for Military Purposes*, op. cit.
[67] Ibid.
[68] The production of 25 kilograms of weapon-grade uranium is taken as requiring roughly 6,000 swus, where the weapon-grade uranium is produced in ideal cascades arranged into four steps, going successively from natural to weapon-grade. This contrasts with the production of weapon-grade uranium in one long ideal cascade, which would have required fewer swu's but is unrealistic. Moreover, inefficiencies in the four step arrangement, including enrichment stoppages, and centrifuge breakage, would increase the required swu, in some cases significantly. Thus, the actual annual production of weapon-grade uranium could be less.
[69] The median estimate derived below is about 11,000 swu, and includes factors of centrifuge inefficiency, so this value should be divided into the 15,000-25,000 swu per year.

3.3 New Centrifuge Plant at RMP

In 2010, India started building what appears to be a second larger centrifuge plant at the RMP site. However, it remains unclear if this new plant is supplementing or replacing the first one.

In an October 5, 2011 *ISIS Imagery Brief*, ISIS highlighted a new building at the RMP under construction adjacent to what is believed to be the original gas centrifuge plant (see figure 5). The new building under construction was assessed as likely to be a new gas centrifuge uranium enrichment plant.[70] However, in 2011, the new centrifuge plant appeared far from completion.

Imagery dated February 2012 showed that overall construction at India's RMP had greatly advanced. It is apparent in the image that the facility is composed of two large rectangular structures that could both house centrifuge cascades. In April 2013 high resolution commercial imagery shows that the building containing the suspected new enrichment facility appears externally to be nearly complete (see figure 6). Three smaller buildings appear to be complete in recent imagery dated April 2014 (see figure 7). However, whether the plant is operational cannot be determined from the image.

Although the similarity between the first and second enrichment buildings is obvious, the new suspected centrifuge plant is larger. The perimeter of this plant is approximately 200 meters by 150 meters,[71] almost double the size of the original enrichment plant. If this new facility is indeed a new centrifuge plant, it is plausible to assume that it will house a much greater number of centrifuges. Consequently, India could have more than doubled its enrichment capacity, if the original building continues to function as an enrichment plant. If not, the new building would still represent a net growth in India's enrichment capacity.

Public information is insufficient to estimate the current enrichment capacity of the RMP, except in very general terms. It could be similar to that of 2010 or more than double that value, assuming in the latter case that newer centrifuges are being installed that are more powerful than those being installed in 2010 (see next section). Based on public information, however, India is likely trying to increase the enrichment output of the RMP and expand its capacity to produce both LEU and HEU.

[70] Paul Brannan, *Further Construction Progress at Possible New Military Uranium Enrichment Facility in India*, ISIS Report, October 5, 2011. http://isis-online.org/isis-reports/detail/further-construction-progress-of-possible-new-military-uranium-enrichment-f/7#images.
[71] Ibid.

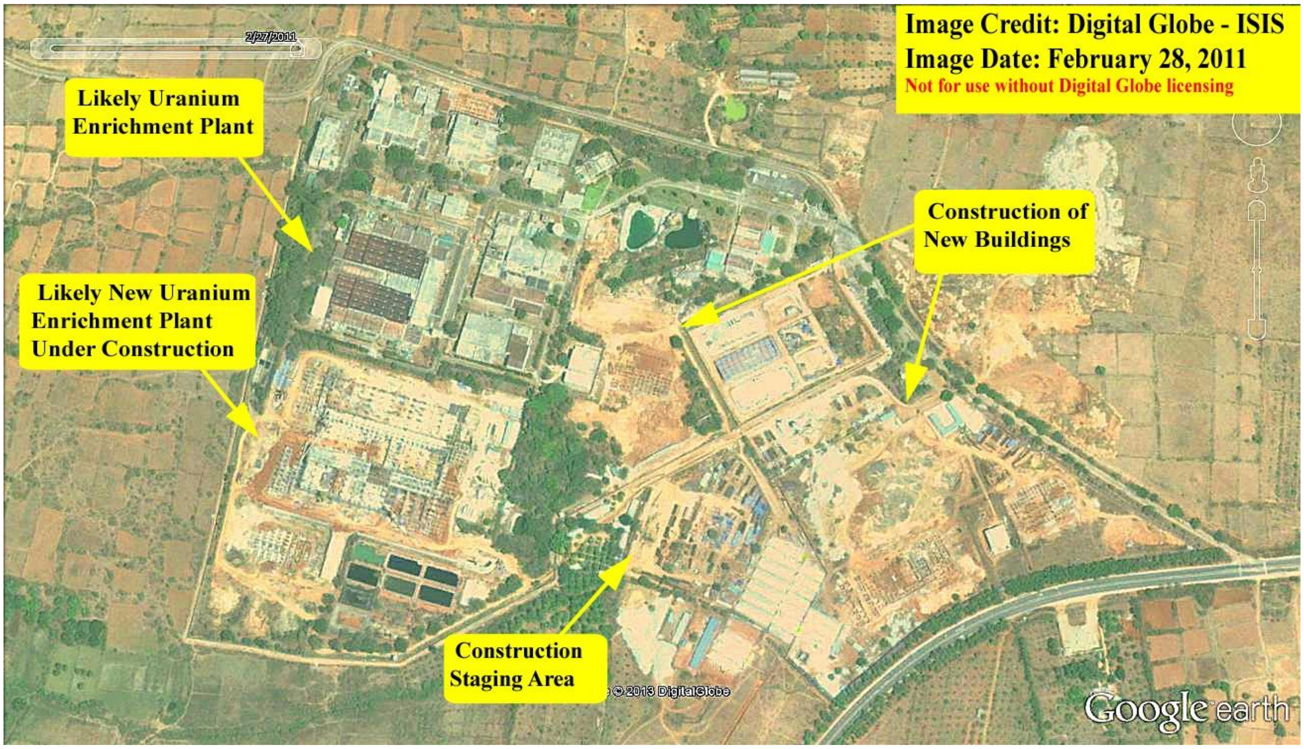

Figure 5. Digital Globe imagery showing the status of India's Rare Materials Plant in February 2011.

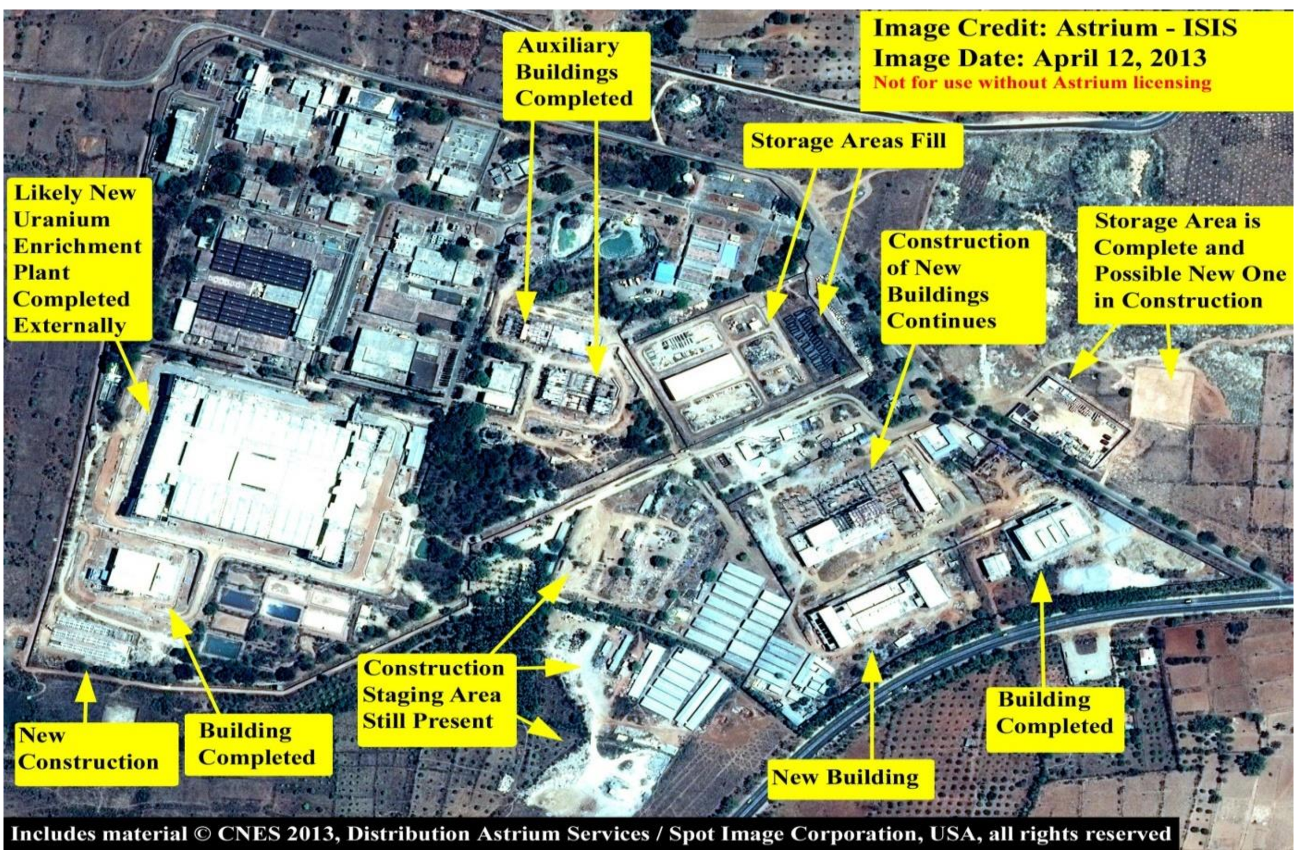

Figure 6. Astrium imagery showing the status of India's Rare Materials Plant in April 2013.

Figure 7. Google Earth imagery showing the status of India's Rare Materials Plant in April 2014.

3.4 Centrifuge Generations and Current Capacity

Uncertainty surrounds the capacity of the centrifuges being currently operated or installed at the RMP. Centrifuge capacities are better known from earlier periods. Combining this information with rare public comments about centrifuge outputs by Indian officials provides some insight into more recent centrifuge enrichment capacities.

In 2008, the head of BARC revealed information about the relative outputs of Indian centrifuges. According to the Director of BARC:[72]

> "The latest fourth generation design, with output 10 times the early design, has been successfully developed and an experimental cascade is in operation at BARC. These would soon be ready for induction at RMP. Third generation design, with 5 times output of early designs, are presently being inducted at RMP."

The official did not identify characteristics of the early or third generation centrifuges. His comments about the "latest fourth generation design" implies that each generation would have several variants. In interpreting this information, the third generation centrifuge, which the official said was then being installed at RMP, is taken as similar in capacity to the ones ordered in 2005 and 2006 and subsequently installed, as discussed above. These centrifuges had estimated single machine outputs of 5-7 swu per year. That would imply that the "early design" had an estimated output of 1.0-1.4 swu per year, making the fourth generation's output 10-14 swu per year. Looking at the comparison in another way, the early centrifuge design is assumed to be the one operating in

[72] Srikumar Banerjee, Director BARC, *Founder's Day Address 2008*, http://www.barc.gov.in/presentations/fddir08.html.

the 1980s, as identified above as a first generation centrifuge with the characteristics of a simple, aluminum rotor centrifuge and an output of about 0.5-1.0 swu per year. That would mean that the output of the third generation centrifuge was 2.5-5.0 swu per year and the fourth generation centrifuge would have a capacity of 5-10 swu per year. This range seems low based on knowledge of the designs in the mid-2000s, although the range's high end, 10 swu/year, overlaps with the low end of the previous estimate of 10-14 swu/year.

Considering both comparisons together, the early centrifuge design may have had an output of about 1.0-1.4 swu/year and the third generation a capacity of 5-7 swu/year. Such an early design would likely have included more than one aluminum rotor tube and at least one bellows. The output of the fourth generation is estimated at about 10-14 swu/year (see table 5). Likely, this centrifuge was deployed on a large scale many years after the 2008 announcement, making it a good candidate for centrifuges being installed today at RMP.

RMP Centrifuge Separative Power (SWU)			
Date		**swu/yr**	**Type and Features**
1980s		0.5-1.0	1st generation machine
Early 1990s?		1-1.4	early generation
2005	Model 1	5	3rd generation[73] with one bellows and maraging steel rotor
	Model 2	7	3rd generation with one bellows and wider diameter rotor
Current		10-14	Fourth generation, maraging steel rotor
Future		20?	Fifth generation, carbon fiber?

Table 5: Centrifuge Separative Power of Machines Deployed at RMP, based on available information.

BARC's Director also announced in 2008 that India was developing a carbon fiber rotor centrifuge and had "achieved a surface speed of 600 m/sec."[74] The development work was in an early stage. "These rotor systems are presently undergoing various trials," he added. This work would allow for significantly faster rotor speeds and thus an expansion in the enrichment output of each centrifuge. However, increasing the speed significantly above that achieved with maraging steel rotors is technologically challenging and likely would take many years to reach the point of being able to deploy these centrifuges on a mass scale.

3.5 Special Materials Enrichment Facility (SMEF)

India is in the early stages of building a larger unsafeguarded centrifuge complex, the Special Material Enrichment Facility (SMEF), in Karnataka. In 2011, India announced publicly its intention to build this industrial-scale centrifuge complex in Challakere Taluk, Chitradurga District (Karnataka).[75] India's top nuclear official said in 2011 that the Special Material Enrichment Facility will not be safeguarded and will have multiple roles, both civilian and military.[76] BARC recently confirmed this dual-use intention and described the facility as a "large scale facility"

[73] The bellows drawings for these models have references to earlier, similar drawings dated in the 1990s, suggesting long research and development timeframes before deployment on an industrial scale.
[74] *Founder's Day Address 2008,* op. cit.
[75] The land for this facility was transferred to BARC in late 2010.
[76] "Enrichment capacity enough to fuel nuke subs," *IBNLive Specials*, Interview with Dr. Srikumar Banerjee, op. cit.

compared to the Rare Materials Project, implying that the new site will also house gas centrifuges.[77] This site could be dedicated to the production of both HEU and LEU for military and civilian purposes. India has reportedly been producing HEU for its nuclear submarine at the RMP and may also intend on producing HEU at the SMEF once it is operational.[78]

Citizens and environmental groups have challenged the siting in Karnataka of this BARC facility and other adjacent facilities being built by India's Defense Research and Development Organization (DRDO) as illegal because of environmental concerns.[79] As a result of the legal actions of the Environment Support Group (ESG), India's National Green Tribunal, which is the government's environmental oversight body, stayed all ongoing work at these sites in August 2013.[80] However, given the continuation of construction, the Tribunal had to re-affirm the halting of all construction in the area.[81] In August 2014 the Tribunal issued its final order in which it ruled that no activity could take place until the agency's had obtained the necessary environmental clearances.[82]

ISIS used publicly available information to locate the SMEF (see figure 8). Commercial satellite imagery showed that BARC had finished some preparatory work at the site, but major construction of this larger centrifuge plant had not yet started.

There is no public information about the planned capacity of the SMEF. However, given that it is intended to provide LEU for nuclear power reactors, its capacity should be expected to involve more than 100,000 swu per year or even be several times this size.

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[77] Statement of objections filed by the Respondent Nos. 10 (Bhabha Atomic Research Centre) and 12 (Defense Research and Development Organization), op. cit. In this document, the purpose of the new facility is stated to be meeting "the future requirement of upgraded fuel for use in power sector as well as other strategic purposes."

[78] Saurav Jha, "Enrichment capacity enough to fuel nuke subs," *IBNLive Specials*, Interview with Dr. Srikumar Banerjee, Chairman of Atomic Energy Commission of India, November 26, 2011, http://ibnlive.in.com/news/enrichment-capacity-enough-to-fuel-nuke-subs/206066-61.html; T.S. Subramanian, "In the event of a nuclear incident, victims must get prompt compensation," *The Hindu*, September 6, 2010. http://www.thehindu.com/opinion/op-ed/article615818.ece.

[79] Leo Saldanha, *Forfeiting Our Commons*, Environmental Support Group Report, June 2013, http://www.academia.edu/3841386/ESG_Report_on_Challakeres_Amrit_Mahal_Kaval_Grasslands_Submitted_to_Expert_Committee_Appointed_by_National_Green_Tribunal.

[80] "National Green Tribunal orders Status Quo on activities of DRDO, BARC, ISRO, IISc, et.al., in Challakere, Chitradurga," Press Release, August 21, 2013, http://www.esgindia.org/campaigns/press/national-green-tribunal-orders-status-qu.html.

[81] "National Green Tribunal halts all construction activity in Challakere Amrut Mahal Kavals," Press Release, February 26, 2014, http://www.esgindia.org/sites/default/files/events/press/esg-press-release-ngt-stays-construction.pdf.

[82] See "Challakere Villagers Overcome BARC lies to Reclaim Amrit Mahal Kavals," Environmental Support Group, November 25, 2014, http://www.esgindia.org/campaigns/press/challakere-villagers-overcome-barc-lies-.html.

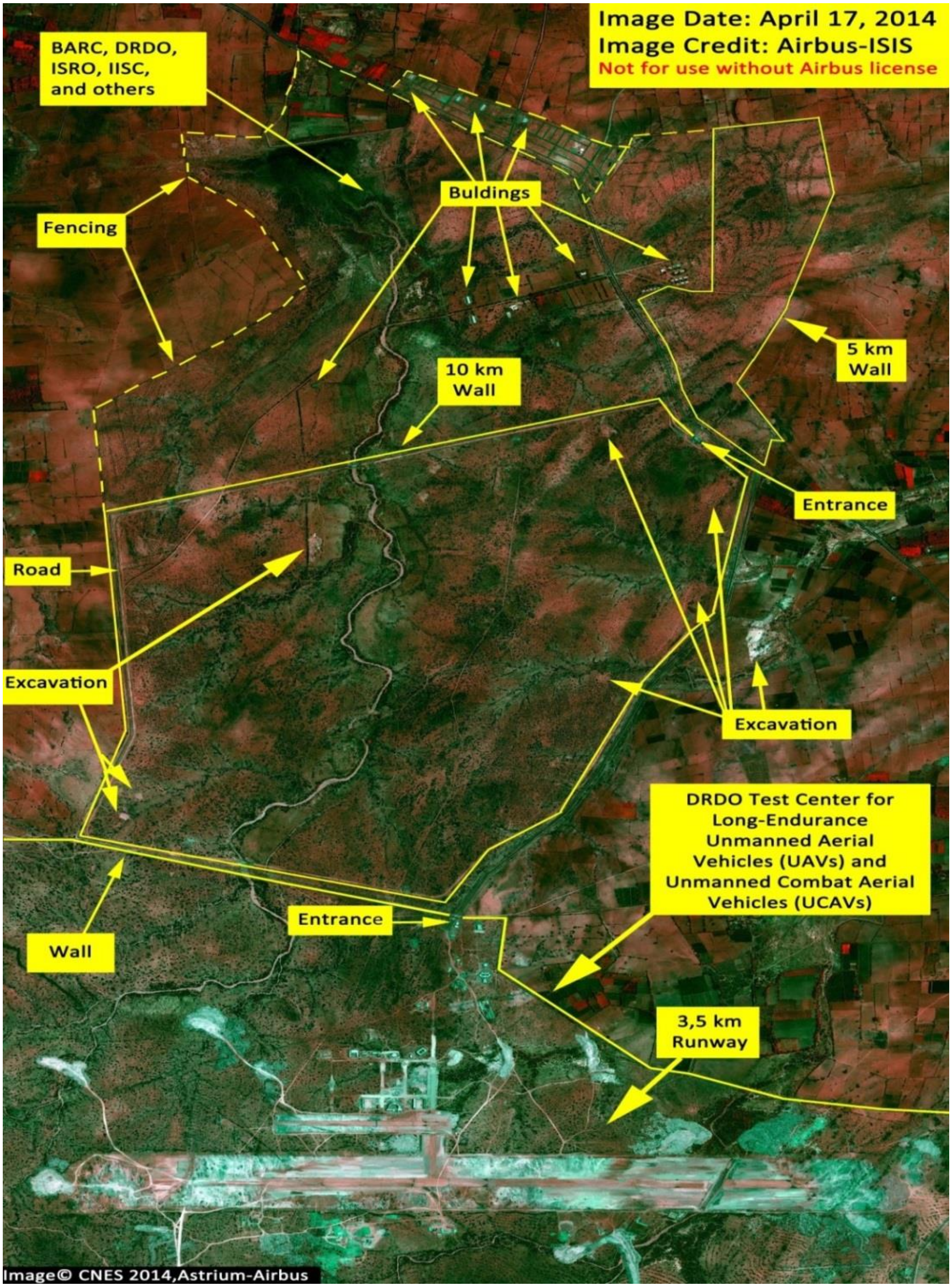

Figure 8. April 2014 Airbus imagery showing how land is being divided up near Khudapura, Chitradurga District, Karnataka.

3.6 HEU Requirements

India has several motivations for making low and highly enriched uranium. Interviews with senior Indian officials show that they felt pressure to match Pakistan's accomplishments with gas centrifuges. More importantly, Indian officials have expressed interest in having an indigenous source of enriched uranium for domestic research and power reactors, thermonuclear weapons, and naval reactors. The RMP does not appear large enough to provide enriched uranium for all of these requirements, particularly enriched uranium for nuclear power reactors, a task that likely must await the operation of the SMEF.

India has reportedly made highly enriched uranium (HEU) at the RMP site, and in 2011 its top nuclear official said this enrichment site is more than adequate for producing enough enriched uranium for its nuclear-powered submarine reactors.[83] This section estimates India's stock of HEU based on evaluating requirements for this material in specific programs. This method is necessitated by the lack of reliable information about the RMP's production of enriched uranium. A limitation of this method is that the RMP may have produced more HEU than estimated below and simply stored it for future use. This estimate does not include HEU in this category.

3.6.1 Naval Reactors

Most of India's enriched uranium capacity has been dedicated to making fuel for its naval reactors. This section estimates the amount of HEU produced for India's naval reactor program and the separative work required for producing this amount of enriched uranium.

India's interest in naval reactors for submarines goes back decades. The naval reactor program, codenamed the Advanced Technology Vessel (ATV), is surrounded by secrecy. BARC is responsible for building the reactor and associated steam generating plant, and military organizations and associated contractors are responsible for building everything else in the submarine.

In August 2006, *The Hindu* reported that the ATV's naval prototype reactor at Kalpakkam was operational. This operational date was subsequently confirmed by BARC.[84]

The prototype reactor is reportedly similar to the one used in the first deployed submarine.[85] "The land-based PWR and the submarine version are on a 1:1 scale. This shore-based reactor has been running smoothly for the past three years," said A. Moorthi, Scientific Officer, BARC, in 2009.[86] It is assumed that the prototype reactor and reactors deployed in the first and second submarines contain the same amount of enriched uranium.

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[83] Saurav Jha, "Enrichment capacity enough to fuel nuke subs," *IBNLive Specials*, Interview with Dr. Srikumar Banerjee, chairman of Atomic Energy Commission of India, November 26, 2011, http://ibnlive.in.com/news/enrichment-capacity-enough-to-fuel-nuke-subs/206066-61.html.

[84] See for example, Srikumar Banerjee, Director BARC, *Founder's Day Address 2009,* October 30, 2009, http://www.barc.gov.in/presentations/fddir09.pdf.

[85] T.S. Subramanian, "PWR building shows indigenous capability, says Kakodkar," *The Hindu*, August 3, 2009, http://www.hindu.com/todays-paper/pwr-building-shows-indigenous-capability-says-kakodkar/article195785.ece.

[86] T.S. Subramanian, "Nuclear Arm," *Frontline*, vol. 26, issue 17, August 15-28, 2009, http://www.frontline.in/static/html/fl2617/stories/20090828261702500.htm.

India has built the *INS Arihant*, its first indigenously produced nuclear-powered ballistic missile submarine (SSBN).[87] The submarine was launched in 2009 and operation was expected within a year. Afterwards, the media reported that by the end of 2012, the submarine would be inducted into the navy.[88] However, the submarine's reactor did not go critical until August 2013.[89] By October 30, 2014, *INS Arihant* had completed most harbor trials and was ready for sea voyage. It started sea trials for the first time on December 15, 2014,[90] and is scheduled to undergo its first missile firing test in 2015. The goal is to introduce the submarine into the navy in early 2016. [91]

By late 2014, the nuclear submarine's first reload core completed cold and hot criticality experiments and associated physics experiments, and was ready for shipping by October 2014.[92] These testing dates would imply that the reactor was originally expected to have its first reload in the not too distant future. With an official launch in 2009, the submarine reactor was expected to have operated far sooner than it has, but the time lag was caused by the complexity of the "platform and its equipment."[93] Given the long lead times in enriching uranium and producing the fuel, however, the first reload may have been ordered when the ship first launched, expecting a reload in about 2015 or in the next few years. These considerations would imply that the first core was expected to last at least five years but probably less than ten years. Here the core lifetime is estimated at 5-7 years.

India has also started the construction of its second and third nuclear-powered submarines that are expected to be inducted over the next five years; it has plans to start the construction of two more for a total of five nuclear powered submarines.[94] One would expect that at least one if not both cores for the two submarines under construction have been ordered.

The naval reactor is a pressurized water reactor. Its compact reactor has several features, according to BARC. It allows for a quick response for power ramping, is fueled with "high fissile containing fuel," and can be submerged for a long period of time, implying a long-life core.[95]

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[87] A nuclear-powered submarine, *INS Chakra*, was already introduced into the Indian Navy in 2012. However, this is a Russian-made nuclear-powered submarine which Russia has leased for ten years. "INS Chakra: Top 10 Must-Know Facts," NDTV, http://www.ndtv.com/article/india/ins-chakra-top-10-must-know-facts-194179.

[88] "India's Nuke Sub Sea Trials Delayed," *The Weekly Voice*," undated, http://www.weeklyvoice.com/headlines/indias-nuke-sub-sea-trials-delayed/.

[89] "Chief of Naval Staff Visits Headquarters Eastern Naval Command," Indian Navy, Press Release, April 30, 2014, http://indiannavy.nic.in/press-release/cns-visits-hqs-eastern-naval-command.

[90] "Nuke-powered sub INS Arihant begins sea trials," *Hindustan Times*, December 16, 2014, http://www.hindustantimes.com/india-news/nuke-powered-sub-ins-arihant-heads-out-for-sea-trials/article1-1296904.aspx; Sandeep Unnithan, "Indigenous Nuclear Powered Submarine INS Arihant to Head out for Sea Trials," *India Today*, December 13, 2015, http://m.indiatoday.in/story/indigenous-nuclear -powered-submarine-ins-arihant-sea-trials-navy-ballistic-missile/1/406718.html.

[91] "India's Indigenous Nuclear Submarine Arihant to Undergo Missile Firing Tests," The Economic Times, October 11, 2015, http://economictimes.indiatimes.com/news/defence/indias-indigenous-nuclear-submarine-arihant-to-undergo-missile-firing-tests/articleshow/49311148.cms.

[92] Sekhar Basu, *Founder's Day Address,* Bhabha Atomic Research Center, October 30, 2014, http://www.barc.gov.in/presentations/fddir14.pdf.

[93] "Indigenous Nuclear Powered Submarine INS Arihant to Head out for Sea Trials," op. cit.

[94] "Indigenous Nuclear Powered Submarine INS Arihant to Head out for Sea Trials," op. cit; T.S. Subramanian, "In the event of a nuclear incident, victims must get prompt compensation," *The Hindu*, September 6, 2010. http://www.thehindu.com/opinion/op-ed/article615818.ece and "India's Nuclear Submarine Force Shaping Up," Defense News, May 18, 2013, http://defencenews.in/defence-news-internal.aspx?id=UkatsKbOlb4=.

[95] *Founder's Day Address 2009*, op. cit.

However, the reactor's design, including its power, is not public. Media reports have listed many different thermal outputs of this reactor, from about 50 up to 150 megawatts-thermal.[96] Most estimates appear to be in range of 80-100 MWth.[97]

The enrichment level of the fuel is also unclear from public reports, although the public information usually gives an enrichment level between about 20 and 40 percent. However, higher enrichments cannot be excluded.

Crystal Ball® software is used to estimate the amount of HEU produced for submarine cores and the enrichment requirement to make this amount of HEU. The latter allows a comparison with available information about the RMP's annual enrichment capacity. The results are ranges, or more accurately frequency distributions of results, based on key variables that are given below as ranges of possible values.

The first part of the calculation estimates the amount of uranium 235 in a submarine core, where each core is assumed to have the same amount of uranium 235 initially. The calculation first builds on the International Panel on Fissile Materials (IPFM) estimate of the uranium 235 content of an Indian submarine core based on properties of nuclear powered submarines and an extrapolation from a Russian naval reactor fueled with weapon-grade uranium.[98] The IPFM experts assumed that the submarine reactor would operate on average for 100 hours per year at full speed and 5000 hours per year at half speed (or one-eighth power). This operation corresponds to the submarine reactor operating about 58 percent of the year, its availability factor. Operation of two thirds of the year appears consistent with standard practices of nuclear navies. Under these assumptions, the reactor's capacity factor would be far lower, only about 8.3 percent. This factor measures the total energy output of the reactor in a time period divided by the total possible energy output in the same period. A lesson of IPFM's assumptions, which appears realistic, is that the capacity factor of a naval reactor is very low. Here, the capacity factor is assumed to be 5-10 percent.[99] The reason is that a typical submarine operates at fairly low speed normally with brief periods of high speed, necessitating a reactor with a relatively high power to achieve those high speeds on demand. The power of the reactor is taken as between 80 and 90 megawatt-thermal. Each megawatt-thermal day of energy requires the consumption of 1.25 grams of uranium 235, where consumption includes fissioning and neutron transmutation of uranium 235. The other variables are fuel burnup, assumed at 30-50 percent,[100] and a reactor lifetime of 5-7 years, as discussed above. There is no public data on the main variables, but these values are consistent with those used by the IPFM and others. The equation for the kilograms of uranium 235 in the core is a straightforward, albeit simple method of estimating the necessary uranium 235.[101] This treatment differs from the IPFM in that it is considering ranges of variables rather than making a single point estimate.

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[96] T.S. Subramanian, "Reactor for nuclear submarine fully operational," *The Hindu*, August 18, 2006. See also 2006 *Founder's Day Address by Director, BARC*, op. cit. and *India's Gas Centrifuge Enrichment Program: Growing Capacity for Military Purposes*, op. cit. However, the larger powers are believed to be inaccurate and reflect uncertainties about the naval reactor in early media reports.
[97] A recent media report put the reactor's power at 83MW, although the basis for this statement was not reported, "Indigenous Nuclear Powered Submarine INS Arihant to Head out for Sea Trials," op. cit.
[98] IPFM, *Global Fissile Material Report 2010, Balancing the Books: Production and Stocks*, IPFM, 2010, pp. 123-124.
[99] Capacity factors greater than ten percent would imply much longer periods at sea or many more days at higher speeds. Neither seems likely or necessary for an Indian submarine.
[100] Fuel burnups of 40-50 percent are typically expected, but with a newly developed reactor the burnups could be lower, at least initially.
[101] The equation is reactor power x capacity factor x 365 days x core lifetime x conversion factor of uranium 235 consumed per unit of energy, all divided by fuel burnup.

The median estimate of the amount of uranium 235 in the core is 39 kilograms, with a range of 17-75 kilograms (see figure 9). The wide range reflects uncertainties in the main variables. Figure 9 shows the distribution of values. The median value is lower than the single point estimate derived by IPFM, which is 65-73 kilograms. Much of the difference reflects that IPFM assumes a ten year lifetime for the core and this estimate assumes a 5-7 year lifetime for each core. The very low and high values are unlikely. The bulk (60 percent) of the results are within 10 kilograms of the median.

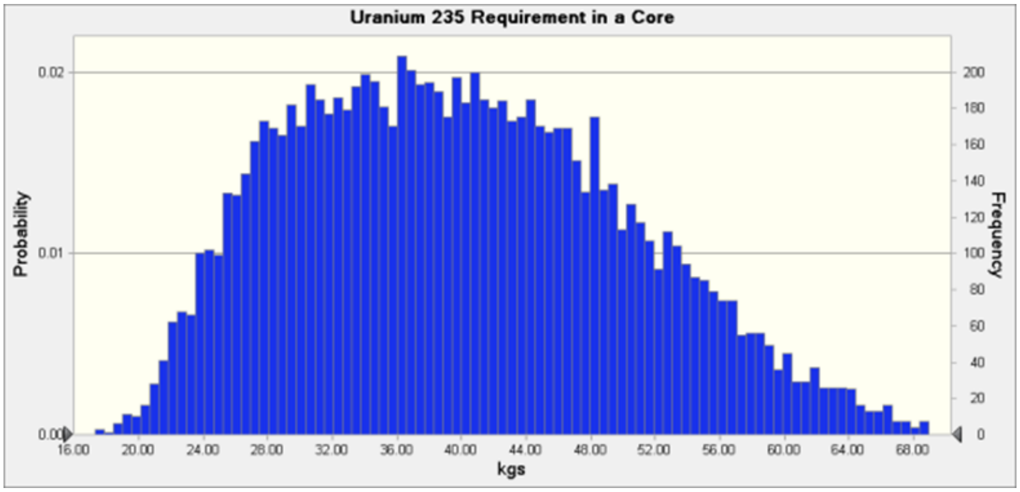

Figure 9. Amount of Uranium 235 initially in a naval core.

With an estimate of the amount of uranium 235 in each core, the total amount of HEU depends on its enrichment level. Here the enrichment of the fuel is assumed to be between 20 and 40 percent. Thus, if all the HEU were 20 percent enriched, the total amount would have a median of 196 kilograms and a full range of be 86-380 kilograms. If all the HEU were 40 percent, the total amount would have a median of 98 kilograms and a range of 43-190 kilograms. One manner to interpret the data is to take a range of the medians, and conclude that a central estimate of India's stock of HEU in a submarine core is 98-196 kilograms, where the enrichment level is between 20 and 40 percent.

To estimate the enrichment output needed to make enough HEU for a core requires a determination of the amount of separative work needed to produce this amount of uranium 235 when in HEU enriched to between 20 and 40 percent. To start, an ideal cascade calculation, with a single long cascade, is used first to derive a course estimate of the amount of separative work necessary to make 20 or 40 percent HEU. Then, this value is corrected by multiplying by an inefficiency factor, which reflects the actual values achieved in practice. Without operational data on Indian centrifuges, data are used from the Iranian and North Korean centrifuge programs and Khan network documentation, which reflects the Pakistani experience. In the calculation the inefficiency factor is based on a dimensionless multiplicative factor of 1.2 to 2.0 (with a reciprocal of 0.5 to 0.83). For a program like India's which has reportedly experienced many problems, this factor appears reasonable absent RMP operational data. Figure 10 shows the distribution in separative work. The median is 11,000 swu, with a full range of 4,000 to 28,000 swu. The wide range reflects uncertainties in the major variables, including the capacity factor and centrifuge inefficiency. However, 70 percent of the individual results are within 4,000 swu of the median.

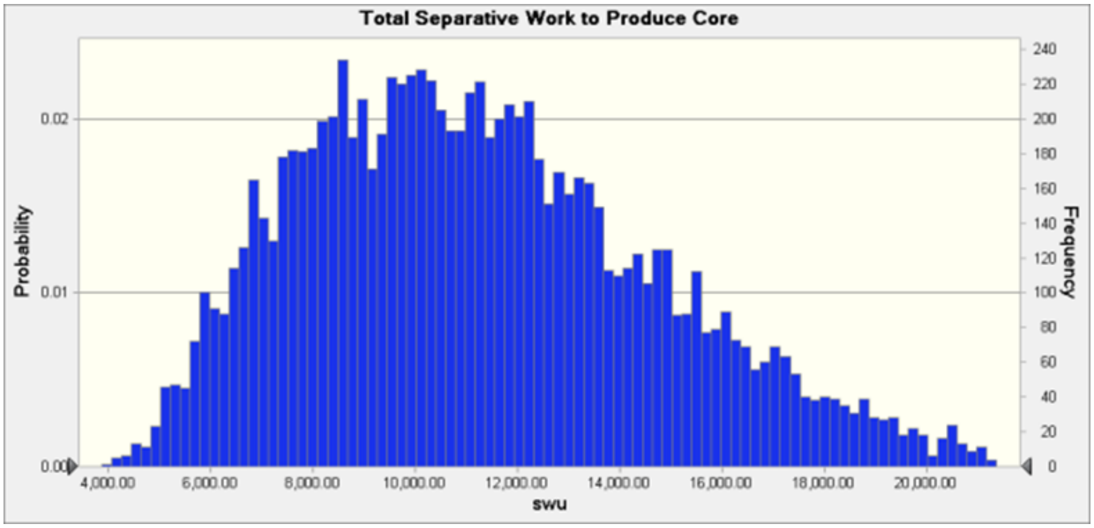

Figure 10. The separative work necessary to produce enough HEU for a submarine core.

The total number of cores produced for the naval reactor program is not known. However, at least three cores are known to have been produced. Enriched uranium for another 1-2 cores may have been made to date (see table 6). The range of 4-5 cores also includes that the HEU for the fifth core could be under production at the end of 2014.

The total amount of HEU produced in these 4-5 cores depends on the enrichment level. If all is 20 percent HEU, the median is 880 kilograms, with a range of 360-1,800. If all is 40 percent HEU, the median is 440 kilograms, with a range of 180-900 kilograms. As before, a central estimate of the total amount of HEU produced for naval reactors is 440-880 kilograms of HEU enriched to between 20 and 40 percent.

The total amount of separative work to make 4-5 cores has a median of 50,000 swu. The full range is 17,000-123,000 swu, where 60 percent of the individual results are within 15,000 swu of the median. The wide range makes it more difficult to discuss the RMP's ability to have made enough HEU for four or five submarine reactor cores. However, considering the more likely individual results, overall the RMP appears to have been large enough to have made this number of cores, which corresponds to a slowly advancing naval reactor program, even assuming periods that witnessed great difficulty in operating centrifuges.

Reactor	Cores	Core Fabricated
Land-based Prototype	Core: operational in 2006	yes
	Refueling: unknown	?
1st Submarine ***INS Arihant***	Core: critical August 2013	yes
	Reload Core: critical October 11, 2014, ready for shipping October 30, 2014[102]	yes
2nd Submarine ***INS Aridaman***	Core	yes
	Reload Core	no
3rd Submarine	Core	?
	Reload Core	no
4th Submarine	Core	no
	Reload Core	no
5th Submarine	Core	no
	Reload Core	no
Total	Cores: between 4 and 5	

Table 6: Estimated cores ordered by the end of 2014.

3.6.2 Thermonuclear Weapons

Indian nuclear weapons have depended on plutonium. However, highly enriched uranium, in particular weapon-grade uranium, is desirable for thermonuclear weapons. Indian officials have stated that the 1998 full-scale nuclear tests included a thermonuclear device. In 2000, Dr. Anil Kakodkar, then Director of BARC, told *The Nation* that a thermonuclear device was tested at a relatively low yield, less than 45 kilotons, because of the proximity of a nearby village.[103] He added, however, that India could design a thermonuclear device of a higher yield.

These discussions have led to speculation that weapon-grade uranium is used in Indian thermonuclear weapons. India is unlikely to want many such devices, so the total amount of HEU dedicated to this purpose would be expected to be relatively small. One uncertainty is whether the RMP is organized in a dedicated manner to make weapon-grade uranium, but this does not appear to be an obstacle. If the weapon-grade uranium is produced in steps, as discussed above, the manufacture and operation of steps to go from intermediate levels of HEU, such as 20-40 percent enriched, is straightforward and involves relatively few additional centrifuge cascades. Thus, production of weapon-grade uranium would not interfere in the routine production of HEU for naval reactors, the priority of the RMP. Faced with a lack of information but evidence that India has produced HEU for nuclear weapons, it is assumed that India has made 100-200 kilograms of weapon-grade uranium for nuclear weapons. Of course, this estimate is highly uncertain.

The amount of WGU in a thermonuclear weapon is typically highly classified. Inadvertent declassifications have revealed that a single-stage thermonuclear device can hold up to 100 kg of weapon-grade uranium and achieve explosive yields of hundreds of kilotons. Two-stage thermonuclear weapons would be assumed to rely on much less WGU. For this estimate, we assume crudely that India has a few to several thermonuclear weapons.

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[102] Kalyan Ray, "Nuke submarine's lease of life extended," *Deccan Herald*, New Delhi, Dec 1, 2013, http://www.deccanherald.com/content/372258/nuke-submarine039s-lease-life-extended.html.
[103] T. S. Subramanian, "A Controversial Decision," *Frontline*, vol. 17, issue 13, June 24-July 7, 2000.

Each such weapon is also assumed to contain plutonium. Thus, given the uncertainties in these calculations, including in the weapon-grade plutonium estimates, the calculated value of the number of India's nuclear weapons is not adjusted up or down to reflect any thermonuclear weapons.

3.6.3 Civil Research Reactors

Some of India's research reactors may have required enriched uranium from the RMP. However, they are not known publicly to have used HEU produced in the RMP. The HEU for the one megawatt-thermal Apsara reactor was imported from Britain and France.

In 1998, India stated that it planned to refurbish the Apsara reactor and covert it to LEU fuel. This reactor was finally closed in 2010 for refurbishment.[104] Table 7 contains an estimate of the remaining HEU discharged from the Apsara reactor (see *Civil HEU Watch*). As far as can be determined, the Apsara reactor did not use HEU from the RMP, although this is unconfirmed. RMP is making low enriched uranium for this reactor, although these quantities are small.[105]

Indian officials have stated plans to build a 20 megawatt-thermal multi-purpose research reactor (MPRR) using LEU (slightly less than 20 percent enriched). LEU for these reactors would likely be produced at the RMP. Total separative work requirements would be a significant fraction of that needed to make enough HEU for a naval core. But this extra requirement would likely not interfere in the RMP's ability to make HEU for naval reactors.[106]

3.6.4 Summary of HEU

India's Total Estimated HEU Stocks, end 2014			
Naval Reactors			
	Cores	HEU (kg)	Range
	4-5	440-880	180-1,800
Thermonuclear Weapons			
	material	Weapon-grade uranium (kg)	Range
	Weapon-grade uranium	150	100-200
Research Reactors			
Apsara	HEU	HEU (kg)	
		5[107]	
TOTAL		440-990	280-1,900

Table 7: HEU Stocks at the end of 2014.

[104] Government of India, Department of Atomic Energy, Bhabha Atomic Research Center, Apsara Reactor, http://www.barc.gov.in/reactor/index.html.

[105] Fabrication of fuel plates for the first core of Apsara was completed by the end of 2014. See *68th Independence Day Address by Director, BARC*, 2014, http://www.barc.gov.in/presentations/20140815.pdf.

[106] The MPRR is expected to supplement India's isotope production capacity to meet the projected requirements of various isotopes beyond the year 2015. In 2009 the reactor was undergoing feasibility studies. However, the current status of this reactor is unclear. See Srikumar Banerjee, *61st Republic Day of India*, Jan-Feb. 2010, http://www.barc.gov.in/publications/nl/2010/2010010202.pdf.

[107] This estimate covers civilian research reactors in India that used HEU fuel. One was the 1 MWth Apsara reactor. See *50 Glorious Years of Apsara,* BARC, 2006. This source states that the Apsara reactor used a total of three cores, each containing about 5 kilograms of 93% enriched uranium. The first two cores were from Britain and the third was shipped by France in 1983. Apparently, the Aspara reactor did not use indigenously produced HEU. The first two cores were sent back to Britain for reprocessing. It is unclear if India owns the recovered HEU or if Britain took ownership, and what was the ultimate fate of the recovered HEU. Here, it is assumes that the HEU was not returned to India.