India's Gas Centrifuge Enrichment Program: Growing Capacity for Military Purposes

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Since the 1970s, India has pursued gas centrifuges to enrich uranium. The history and current status of India's gas centrifuge program has been a long-held state secret. Nonetheless, ISIS sought to investigate this program using open sources and information from interviews with Indian and other government officials.

This report traces the history of India's centrifuge enrichment program and assesses its current and projected enrichment capacity based on publicly available procurement data and other publicly available information, which were analyzed using specialized software. Our conclusion is that India is currently operating between 2,000 and 3,000 centrifuges at the Rare Materials Project (RMP), India's primary centrifuge enrichment facility approximately 19 kilometers outside of Mysore. We also conclude that India is currently seeking to double the capacity of RMP

The Indian Department of Atomic Energy (DAE) commissioned India's main enrichment plant, codenamed the Rare Materials Project (RMP), around 1990. In addition to a gas centrifuge facility, this site may also contain a uranium hexafluoride production facility. By 1997, after several years of difficulty, India seems to have achieved a technical breakthrough at RMP. Although India has experienced difficulties in building centrifuges, they now appear to be competent at constructing centrifuges comparable to those common in Europe in the 1970s. India is currently attempting to expand the number of centrifuges at RMP by 3,000, increasing its capacity by at least 15,000 separative work units (SWU) per year, a common measure of the output of a uranium enrichment plant.

The Indian government has proposed to designate its gas centrifuge enrichment facilities, such as RMP, as military sites under the framework of US-India nuclear cooperation. Thus, India is unlikely to use these facilities to create fuel for the Tarapur boiling water reactors, which will be designated as civilian facilities. India is currently importing sufficient amounts of low enriched uranium (LEU) to fuel the Tarapur reactors. These reactors could have otherwise absorbed the RMP's capacity.

As a result of its recently acquired ability to import LEU, India can devote the enrichment capacity of RMP to highly enriched uranium (HEU) for military applications. India would most likely use the HEU for fuel in submarine reactors and thermonuclear weapons.

Early Gas Centrifuge Effort

The Bhabha Atomic Research Center (BARC) at Mumbai created India's first gas centrifuge facility. By 1986, this facility reportedly contained about 100 centrifuges operating in a cascade and enriched uranium up to about two percent uranium 235.[1] Centrifuge research activities at BARC are believed to continue.

In the early 1980s, India decided to build the larger facility near Mysore.[2] The DAE's original goal was reported to have about 5,000 operating centrifuges at RMP, but technical problems prevented them from reaching this goal.[3]

Construction of RMP, 1986

By 1986, the DAE began construction of the RMP at a remote site approximately 19 kilometers outside of Mysore.[4] Figure 1 is a commercial satellite image of the RMP from April 25, 2005.[5]

By mid-1987, the DAE sought contractors to install electrical wiring, street lighting and lightning protection. The DAE has not revealed RMP's official commission date, but it is believed to be about 1990.

Since 1984, India has procured for RMP through the DAE "front company" Indian Rare Earths (IRE) Ltd. IRE does not have the technical expertise to build or operate a gas centrifuge plant and is publicly responsible for mining and refining rare earths. In reality, BARC oversaw the personnel and operations of RMP. While IRE mentioned RMP in its public procurement advertisements from 1984 to 1985, it began omitting the phrase "RMP" from these advertisements after 1985. Except for an apparent mistake in 2004, IRE's public advertisements to buy equipment did not make further reference to RMP or Mysore.

India depended extensively on foreign procurement of equipment and materials for the RMP. BARC personnel frequently traveled to Europe to arrange and oversee procurement of key items for RMP from suppliers. Senior BARC official, Shri Bishweswar Bhattacharjee, arranged procurements for RMP and was the liaison between BARC, IRE and European suppliers. Another major BARC participant in the European purchases in the 1980s was T.K. Bera, who was a senior manager of RMP in the 1990s.

Beginning in 1985, RMP began to receive manufacturing equipment and materials from German, Swiss, and French companies. During this period, overseas procurements for RMP included a flow-forming machine from Leifeld, a currently defunct German firm that was

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[1] 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.

[2] "Keeping the Nuclear Option Open," op. cit.

[3] "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.

[4] At this time, RMP's procurement company placed orders for outdoor piping for utilities and service lines at the site.

[5] A 1988 advertisement from Indian Rare Earths invited a contractor to build a facility at RMP, called Building Number 10. The advertisement specified that the construction would take place 19 kilometers from Mysore on Hunsur Road. An IRE advertisement dated September 2000 mentioned RMP explicitly and specified the construction of a new pulsed power secure fence with a total length of 2,500 meters. The circumference of the outer fence of the facility in the image is about 2,500 meters and the facility in the image is 19 kilometers west of Mysore on Hunsur Road.

capable of producing equipment to make maraging steel centrifuge rotors. India sought vacuum pumps, valves, vacuum measuring equipment, vacuum furnaces, a mass spectrometer, welding equipment, including an electron-beam welding machine, and small items that can be used as subcomponents for motor stators and centrifuge bearings. IRE ordered sufficient amounts and types of equipment for a plant containing thousands of centrifuges. This capacity is consistent with media reports at the time. BARC or Indian contractors and manufacturers may have made major centrifuge components in India, although the manufacturing equipment and some of the raw materials came from abroad.

India restricted foreign suppliers' access to RMP facilities, probably to prevent the suppliers from gaining information about the centrifuges at RMP. In the late 1980s, for example, a foreign supplier's technician went to India to fix equipment that his company had improperly manufactured. The Indians brought the equipment outside RMP to a guest house and the technician fixed the equipment there.

Available information about DAE centrifuges shows that its centrifuges are similar to centrifuges developed by the European gas centrifuge consortium Urenco. It is unknown whether India used only publicly available information about Urenco's centrifuges or somehow obtained sensitive centrifuge design information. European suppliers may have provided India with centrifuge designs or information about designing centrifuge cascades, in particular cascade piping arrangements and feed and withdrawal stations. Items sought by India in the 1980s appeared to be for auxiliary systems that looked similar to ones used in Urenco plants.

In at least one case, India procured through individuals who also played key roles in the illicit nuclear trading network led by the Pakistani A. Q. Khan. In the late 1980s and early 1990s, according to the 2005 South African indictment of Daniel Geiges and Gerhard Wisser issued by the Transvaal Provincial Division of the High Court of South Africa, Wisser, the founder and former head of Krisch Engineering, "commissioned one of his employees to produce flow meter units which were specifically designed for a uranium hexafluoride application" and had them delivered to India. The fact that the units were suitable for use with uranium hexafluoride strongly implies their intended use in the Indian gas centrifuge program. Because the customer encountered problems with the units, Wisser sent the employee to India to make adjustments. South African court documents also raise the possibility that Krisch Engineering arranged for the delivery of other sensitive items to the Indian centrifuge program, including vacuum measuring equipment and feed and withdrawal equipment for centrifuge cascades.

Problems in the RMP, Early 1990's

Despite the extensive purchase of equipment in the 1980s and 1990s, India encountered serious technical difficulties in building and deploying centrifuges. In its early years, the RMP appears to have been plagued by technical problems.

Up until the mid-1990s, the plant experienced frequent breakdowns and many centrifuges are believed to have failed.[6] In an interview with one of the authors in March 1992 at the Atomic Energy Commission (AEC), P. K. Iyengar, then Chairman of the AEC, acknowledged that India had a centrifuge plant devoted to development of centrifuge technology. He downplayed its size and added that the plant operated intermittently. His comments implied that RMP had already produced enriched uranium.

US government publications also verify the RMP's intermittent operation. An unclassified but confidential report on the Indian AEC, prepared in late 1992 or early 1993 by a knowledgeable US official based in Delhi, claimed that Iyengar had characterized the RMP as inefficient and troubled by frequent breakdowns. The report quoted other knowledgeable Indians as saying that the plant was plagued by frequent problems caused by corrosion and failure of parts. They point out that the facility was experimental, the centrifuges were developed and manufactured without direct external assistance and it was dependent on materials only marginally sufficient for use in centrifuges. The declassified and redacted July 1993 *Report to Congress on Status of China, India, and Pakistan Nuclear and Ballistic Missile Programs* also expressed these views and stated that the RMP had started "limited operations" but was "beset by technical difficulties."

The unclassified US report on the Indian AEC quoted Iyengar as stating that the RMP could enrich uranium up to 30 percent. To have this level of enrichment, the plant either had at least two or three cascades in operation or was batch-recycling the product back into the cascades to bring the level of enrichment up to 30 percent. In either case, the plant would likely have been able to make only small amounts of HEU.

During the 1992 interview, Iyengar refused to divulge details of the centrifuge design. However, he said that the centrifuges at the plant did not have bellows, a specialized component developed by Urenco to permit a longer centrifuge with a higher separative output. Such a centrifuge is called supercritical. Iyengar's comment about the bellows suggests that the centrifuges at RMP had relatively short rotor tubes and were subcritical centrifuges. Media reports stated that the centrifuge rotors used maraging steel produced domestically at the Ministry of Defense enterprise Mishra Dhatu Nigam Limited (MIDHANI) in Hyderabad. Based on the centrifuges being subcritical and having maraging steel rotors, media reports stated that each centrifuge during this period likely had a separative capacity of less than three SWU per year.[7]

By the mid-1990s, the RMP was reported to have several hundred operating centrifuges.[8] Assuming that each centrifuge was subcritical and had an output of about 2-3 SWU per year, the capacity of the RMP would have been about 600-1,500 SWU per year where several hundred centrifuges are taken as 300-500 centrifuges.

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[6] D. Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium, World Inventories, Capabilities, and Policies* (Oxford University Press and SIPRI: Oxford, 1997), pp. 269-271.
[7] See for example, Mark Hibbs, "Second Indian Enrichment Facility Using Centrifuges in Operation," *Nucleonics Week*, March 26, 1992; and "India to Equip Centrifuge Plant with Improved Rotor Assemblies," *Nuclear Fuel*, December 1, 1997.
[8] *Plutonium and Highly Enriched Uranium*, op. cit.

Iyengar's comment did not mean that India was not developing supercritical centrifuges. In a March 1992 interview in New Delhi with one of the authors, former AEC chairman Raja Ramanna suggested that India was already working on supercritical centrifuges. In that interview, Ramana said that the supercritical centrifuges would suddenly shake and create "quite a noise" when passing through resonances. A recent design drawing of a key component of a supercritical centrifuge has an annotation that the more current drawing supersedes a 1992 drawing, implying that BARC was designing and possibly testing supercritical centrifuges at that time. IRE also requested specialized testing equipment in August 1992 associated with the construction of bellows in a centrifuge rotor.

Breakthrough and Expansion

Technical Breakthrough: 1997 to 2002

A sudden increase in procurements of centrifuge-related items in almost identical quantities occurred between 1997 and 1999, suggesting an intention to increase the quantity of centrifuges at RMP. IRE had previously sought several items in hundreds of quantities that appear to be parts of centrifuge subcomponents, such as stator motors, bottom bearings, and valves, and it began to seek them in quantities ranging from 1,500-2,000. These orders could mean that the program intended to build that many centrifuges, although the actual quantity of centrifuges built and successfully operated would be less.

This uptick in procurements of centrifuge subcomponents corresponded with an announcement by Indian officials that the centrifuge program had overcome some of its technical problems. In December 1997, *Nuclear Fuel*, quoting a knowledgeable Indian official, reported that the centrifuge project would build and install improved rotor assemblies with design features aimed at overcoming mechanical limitations.[9]

It is difficult to determine the success of this effort. India has tried to give the impression of great success. BARC publications have showered credit on Bhattacharjee, former director of the RMP and director of the Chemical Engineering and Technology Group (CETG), which handles the centrifuge program.[10] After being promoted in 2001 to director of BARC, media reports and BARC publications stated that he led the team that designed, installed, commissioned and upgraded the "high speed rotor" project, better known as the gas centrifuge effort, required for producing "some of the materials of strategic importance." In a 2001 *Frontline* interview, Bhattacharjee said that the Indian centrifuge program was advancing.[11] He added: "We are developing more and more advanced models of gas centrifuges." Typically, centrifuge programs focus on increasing enrichment output by

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[9] "India to Equip Centrifuge Plant with Improved Rotor Assemblies," op. cit.
[10] CETG appears to be the main organization within BARC responsible for centrifuges. The group includes the Chemical Technology Division (CTD), which partakes in centrifuge research, development, and manufacturing for RMP. CTD includes the Experiment Studies Section, Materials Development Section, and Manufacturing Technology Section
[11] "Sanctions Act as a Catalyst," Interview with B. Bhattacharjee, *Frontline*, Volume 18, Issue 24, November 24-December 07, 2001.

developing centrifuge rotors that are longer and spin faster. As mentioned earlier, India has lengthened its centrifuges by adding bellows. In addition, an Indian media report from 2001 confirmed that RMP had produced "weapons grade fissile material."[12]

A short biography of Bhattacharjee published in the May-June 2001 *India Today* stated that the development work associated with RMP enhanced the nation's engineering capabilities in general and precision engineering in particular. In addition, this project led to the indigenous production of equipment and materials that had earlier been imported. Bhattacharjee's statement suggested that the centrifuge program had successfully reverse-engineered several finished items originally obtained overseas. Despite denials by Indian officials, India continues to seek finished items and subcomponents of finished items from foreign suppliers for its gas centrifuge program.

Estimates of RMP's capacity performed by M.V. Ramana support the view that the number of centrifuges at RMP, including supercritical centrifuges, increased in the late 1990's. In 2004, M. V. Ramana published an estimate of RMP's 1999 capacity.[13] His estimate was based on open source information and an assumption that the main purpose of the RMP up to 1999 was to produce the first core of a naval reactor, estimated at 90 megawatts-thermal. In 1999, his estimate of RMP's capacity was 3,000–7,000 SWU per year. Ramana's estimate would be consistent with the operation of about 1,000-2,000.

Expansion: 2003 to 2006

An Indian media report from December 2004 stated that the capacity and performance of RMP had improved greatly in recent years.[14] Interpreting this statement remains difficult, but it implies that BARC has added centrifuges to RMP and that the RMP has started to produce enriched uranium on a regular basis.

Procurements from 2003 to 2006 indicate that India plans a further expansion in the number of centrifuges at RMP. During this time, there was an increase of orders of centrifuge parts, including multiple orders of aluminum tubes, rotor tubes, bottom bearing subcomponents, and subcomponents for motor stators and valves. There were also efforts to buy vacuum pumps that are capable of handling uranium hexafluoride.

There is no sign of weakening government commitment to RMP. Indian government budgetary documents for 1999-2004 list the RMP as receiving continuing funding.

The site itself has continued to seek new employees and has undergone renovation and expansion. In December 2004, BARC publicly invited applications for forty-five scientific and engineering trainees at RMP. Ten of the selected applicants would need to be mechanical, chemical or electrical engineers with only Bachelor of Science degrees in

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[12] Arunkumar Bhatt, "New BARC Chief Assumes Charge," *The Hindu*, April 4, 2001, accessed at www.hinduonline.com/today/stories/0204000f.htm on October 20, 2004.
[13] M. V. Ramana, "An Estimate of India's Enrichment Capacity," *Science and Global Security*, 12:115-124, 2004.
[14] R. Ramachandran, "Fuel for TAPS," *Chennai The Hindu*, December 18, 2004.

Engineering. Thirty-five technicians would be required to have pre-existing training in chemical plant operation, instrumentation or electronics. BARC itself issued public advertisements from 2004 through 2006 to invite repairs, modifications, and extensions of several buildings and annexes at RMP.

Recent Orders for Supercritical Centrifuges

In late 2005 and early 2006, IRE ordered 3,000 maraging steel tubes with a single bellows in the middle of each tube. Several centrifuge experts in the United States and Europe determined that these tubes are most suitable as supercritical centrifuge rotor tubes. Although the manufacturer of these tubes is unidentified, these orders provide a window into the future expansion of RMP and the types of centrifuges India is building at this site.

These centrifuge parts have characteristics of centrifuges developed by Urenco, the European enrichment consortium. The shape of the Indian rotor tube and the bellows at the middle of the tube are prototypical of Urenco rotors. However, the dimensions and thicknesses of its newest centrifuge differ slightly from early Urenco centrifuges. It cannot be excluded that India may have obtained Urenco designs and modified the designs to suit its needs and manufacturing capabilities. For example, India may have increased the thickness of a tube or bellows because of problems making thinner pieces.

In one case, IRE solicited 2,000 rotors and bellows made from 350-grade maraging steel with exacting specifications typical of centrifuge rotors. These thin-walled tubes have a diameter of 150 millimeters, a wall thickness of less than one-half millimeter, and a finished length of 1,215 millimeters. This centrifuge rotor is similar to the rotor in a G2-type centrifuge which was built by Germany for Urenco in the early 1970s and has a diameter of 145 millimeters as well as a slightly thinner wall. The Indian bellows is similar to a Urenco bellows, but it has a thicker wall and has a slightly different shape. This rotor is likely to have a more difficult time passing through a key resonance and is likely to fail more frequently. The enrichment output of this design is about five SWU per year, implying that DAE plans to increase the capacity of RMP by about 10,000 SWU per year using this centrifuge.

In the second case, IRE solicited 1,000 350-grade maraging steel rotors, each with one bellows, but with a longer and wider rotor tube. These rotors have a diameter of 190 millimeters and a finished length of 1,500 millimeters. BARC may have selected this greater diameter to allow the final length to increase to 1,500 millimeters, which would result in a higher enrichment output for each centrifuge. Thus, the second order may represent an improved centrifuge, although the bellows design remains the same as in the first order. Its output is about seven SWU per year, implying that DAE plans to increase the capacity of RMP by about 7,000 SWU per year using this centrifuge.

In total, these two orders suggest that DAE is aiming to increase RMP's capacity by about 17,000 SWU per year over the next several years. Other information suggests that RMP's capacity could be increased even further. For example, IRE may have ordered more rotors with a diameter of 190 millimeters but not announced the tender publicly. This conclusion is based on a 2005 solicitation made by IRE for aluminum tubes with dimensions that could imply that they would be cut and made into molecular pumps for a centrifuge with a 190millimeter rotor. (A molecular pump is a non-rotating part which reduces the leakage of uranium hexafluoride gas from the rotor.) Assuming a standard length of a molecular pump, the tubing would be sufficient for about 2,000 centrifuges of this type. This suggests that IRE may have sought 2,000 rotors with a diameter of 190 millimeters, instead of only 1,000 such tubes.

The failure rate of the Indian centrifuge is unknown, although the cumulative experience of the Indian centrifuge program would suggest that the failure rate is manageable but unlikely to match Urenco's rate for similar centrifuges. As a result, the future deployed capacity implicit in these two orders for rotors is estimated to be about 15,000 SWU per year.

Estimated Current and Future Capacity of RMP, 2006

India has provided limited public information on the current enrichment capacity of RMP, but a combination of previous estimates and fresh information sheds new light on its capacity and output.

This estimate of RMP's current capacity is performed using Crystal Ball®, a software that permits a more transparent uncertainty analysis. The information compiled for this report allows us, with reasonable certainty, to assume that the RMP has between 2,000 and 3,000 operating centrifuges. In the calculation, this range is represented by a uniform distribution, meaning that each value between 2,000 and 3,000 has an equal probability of being true. Because the plant may contain both subcritical and supercritical centrifuges, the distribution of the capacity of each centrifuge is more complicated. This estimate assumes that the probability of a centrifuge having a capacity of 2-3 SWU per year is about 40 percent and the probability of a centrifuge having a capacity of 4-5 SWU per year is about 60 percent. This means that about 40 percent of the centrifuges are subcritical and about 60 percent are supercritical, with the latter being the type with a diameter of 150 millimeters. This distribution reflects that BARC has been installing supercritical centrifuges at RMP since the late 1990s. The estimated total capacity has a median of about 9,600 SWU per year, with 5^{th} and 95^{th} percentiles of about 5,000 and 13,000 SWU per year, respectively.

The two recent orders for 3,000 supercritical rotors imply that RMP will undergo a significant expansion over the next several years. The capacity implicit in these orders is 15,000 SWU per year. If added to RMP, the future total capacity of RMP is estimated to have a median of about 25,000 SWU per year, with 5^{th} and 95^{th} percentiles of about 20,000 and 30,000 SWU per year, respectively.

Enriched Uranium Needs

India has several political and technical 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 the Tarapur reactors. India's recent actions to import low enriched uranium for the Tarapur reactors underscore this conclusion.

Naval Reactors

India's interest in naval reactors for submarines goes back decades. More recently, it has concentrated on operating a naval propulsion prototype reactor near Kalpakkam and launching an indigenous nuclear-powered submarine that will use a miniaturized version of this reactor. The naval reactor program, codenamed the Advanced Technology Vessel (ATV), is surrounded by secrecy. BARC is reported to be responsible for building the reactor, 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 fully operational and running at its full capacity of 100 megawatts.[15] Most media reports had stated that the naval prototype reactor would have a power of about 40-55 megawatts-thermal and would use HEU enriched to between 20 and 40 percent. Some reports, however, stated a greater power of between 90 and 150 megawatts-thermal. It is likely that the reactor started around 2004.[16]

The purpose of this reactor is likely to test reactor concepts and fuel and to train operators of the submarine reactor. As a result, the prototype reactor core probably does not contain as much fuel as a naval reactor on a submarine. Submarine reactors are usually designed to hold as much fuel as practical to reduce the need to refuel the reactor. The prototype reactor would require about 30-60 kilograms of fresh uranium 235 each year, assuming that it operates at full power for 25-50 percent of the year.[17] If this fuel is 30 percent enriched, the annual requirement would be 100-200 kilograms of HEU per year.[18] Thus, the production of 100-200 kilograms of HEU enriched to 30 percent would require roughly 5,600-11,000 SWU per year.

The RMP most likely produces HEU for submarine reactor cores. The Indian submarine reactor is assumed to have a reactor with a total power of about 100 megawatts-thermal.[19] To increase the time between refueling of the submarines to about 5 years, the submarine

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[15] T.S. Subramanian, "Reactor for nuclear submarine fully operational," *The Hindu*, August 18, 2006.

[16] Media reports have been ambiguous as to the start date of the reactor. Reports in mid-2004 stated that the reactor was approaching completion [See, for example, Rahul Bedi, "Russian Help Bolsters N-Submarine Project," *Bangalore Deccan Herald*, June 7, 2004]. A late 2004 report stated that the "compact" reactor using 25 percent enriched fuel had recently gone critical [R. Ramachandran, "Fuel for TAPS," *The Hindu*, December 18, 2004]. These reports contradicted a series of reports from the late 1990s and early 2000s that the reactor was already operating. The resume of a young mechanical engineer found on the internet tends to support the reports that the prototype reactor was under construction at least through late 2003. This person listed himself as a "supervisor" of various construction activities between mid-2000 and October 2003 at the prototype reactor project (submarine) at Kalpakkam under the Department of Atomic Energy.

[17] These estimates use a burnup of 40 percent.

[18] The amount of separative work required to produce HEU containing 30-60 kilograms of uranium 235 depends on the actual enrichment level and tails assay.

[19] Ramana, "An Estimate of India's Enrichment Capacity" op. cit.

reactor would require about 100 kilograms of uranium 235 in HEU enriched to 30 percent, or about 330 kilograms of HEU.[20] Production of this amount of HEU would require about 18,500 SWU. This HEU is assumed to be produced over five years, for an average annual requirement of about 3,700 SWU per year.

Thermonuclear Weapons

Indian nuclear weapons have depended principally on plutonium. However, highly enriched 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.[21] He added that India could design a thermonuclear device of a higher yield. These discussions imply that India uses the RMP to make HEU for its thermonuclear weapons.

Civil Research Reactors

Some of India's research reactors may require enriched uranium fuel from RMP. The Apsara research reactor, with a maximum power of one megawatt-thermal, may have used kilogram quantities of indigenously produced HEU.

In 1998, India stated that it planned to refurbish and convert the Apsara reactor to LEU fuel and operate the reactor regularly at one megawatt-thermal.[22] As of 2003, work was continuing on the conversion.[23] Indian officials have stated plans to build a 20 megawatt-thermal multi-purpose research reactor (MPRR) using LEU that would be enriched to slightly less than 20 percent. LEU for these reactors would likely be produced at RMP.

Tarapur Reactors

In the early 1990s, Indian officials stated that the two Tarapur boiling water reactors could be loaded with LEU indigenously produced. However, this option was not practical because the RMP was too small to produce enough LEU to fuel either of these reactors. Instead, India opted to obtain LEU from overseas. Bhattacharjee said in the 2001 interview that India intended to continue buying LEU from overseas for the Tarapur reactors.[24] Based on recent events, this strategy has succeeded.

Domestic LEU production for the Tarapur reactors remains unlikely. The reactors would require roughly 15 tonnes of 2-3 percent enriched uranium per year. This amount of LEU would require about 25,000-51,000 SWU per year, assuming a tails assay of 0.3 percent.

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[20] The submarine reactor would be expected to operate with a lower capacity factor than the prototype reactor. The submarine reactor would likely maintain a significant power reserve for situations requiring travel at greater speed.

[21] T. S. Subramanian, "A Controversial Decision," *Frontline*, vol. 17, issue 13, June 24-July 7, 2000.

[22] V. K. Raina, *et al*, "Refurbishment, Core Conversion, and Safety Analysis of Apsara Reactor," Paper presented at the 1998 International RERTR Meeting, October 18-23, 1998, Brazil.

[23] See http://www.dae.gov.in/publ/AR-2003-04/pdf/ch5.pdf

[24] "Sanctions Act as a Catalyst," Interview with B. Bhattacharjee, op cit.

Taking Stock

Table 1 lists the estimated annual requirements for naval reactors and research reactors over the next several years. This assumes that RMP will not make any LEU for the Tarapur reactors. In this case, the annual requirement is estimated to be about 9,400-14,800 SWU per year, where the Indian program produces fuel for one submarine reactor core every five years.

If the actual capacity of RMP is at the upper range of the estimate, RMP should be able to fulfill the requirement for enriched uranium for its reactors roughly on the schedule postulated in Table 1. If the actual capacity is at the lower end, India may not be able to produce enough HEU for its naval reactor program until it expands RMP.

India appears to need most of RMP's capacity for the naval program and, unencumbered by the demands of the Tarapur reactors, can allocate more HEU to naval reactors and thermonuclear weapons. And, notwithstanding the HEU demands of the naval program, RMP could also have produced enough HEU for the thermonuclear test device used in 1998 and a more recent, small set of thermonuclear weapons. Assuming that India assigns 10,000 SWU per year to the production of HEU for thermonuclear weapons, RMP would need to make enough HEU for a few such weapons per year.

HEU Stock

The total amount of HEU produced is difficult to estimate. Most of the current stock of HEU has been produced for the naval reactor program.

Over the last decade, the RMP may have produced both LEU and HEU. RMP likely produced enough HEU for the submarine reactor, two to three years of operation of the prototype naval reactor and an unknown amount of nuclear weapons. These requirements are, respectively, about 200-600 kilograms of HEU (30% enriched), about 330 kilograms of HEU (30% enriched) and several tens of kilograms of HEU. Therefore, as of the end of 2006, the estimated Indian HEU stock is about 550-950 kilograms.

Conclusion

Great uncertainty surrounds India's gas centrifuge enrichment program. After many years, India appears to have finally developed the capability to build and operate a centrifuge plant. It appears on the verge of adding at least 3,000 centrifuges to RMP in addition to about 2,000 – 3,000 existing centrifuges. This would significantly expand India's ability to make HEU for its military nuclear programs and enable it to add a substantial number of thermonuclear weapons to its arsenal.

Although the program has developed with the support of domestic suppliers, it is still seeking foreign suppliers for several key items. If the Nuclear Suppliers Group makes an exception for India, foreign suppliers of dual-use items will need to exercise extra care to ensure that

RMP is not the ultimate end user or beneficiary of exports intended solely for peaceful, non-military uses.

Table 1. Estimated Annual Indian Enriched Uranium Requirements, 2006

Purpose	Annual Requirements	Annual SWU Requirements
Currently known reactor requirements		
Naval Reactors*		
Prototype Reactor	15-30 kg U-235 in HEU	5,600-11,000
1st Sub Reactor**	20 kg U-235 in HEU	3,700
Apsara Research Reactor	<0.6 kg U-235 in HEU	<100
	Subtotal	**9,400-14,800**
Future reactor requirements		
Multipurpose Research Reactor (MPRR)***	11 kg U-235 in LEU	2,000
	Total	**11,400-16,800**

Comments

* The enrichment level of HEU produced for naval reactors is believed to be about 30 percent. Thus, an annual requirement of 30-60 kilograms of uranium 235 corresponds to 100-200 kilograms of HEU enriched to 30 percent.

** The first nuclear powered submarine reactor is assumed to have a reactor with a total power of 90-100 megawatts-thermal. To increase the time between refuelings to 5 years, the submarine reactor is estimated to require on order of 100 kilograms of uranium 235 in HEU (30% enriched), or 330 kilograms of HEU. Production of this amount of HEU would require about 18,500 SWU. This HEU is assumed to be produced over five years, for an average annual requirement of about 3,700 SWU per year.

*** India plans to build the multi-purpose research reactor (MPRR), although construction is not believed to have started. Thus, the enriched uranium fuel has probably not yet been made for the first core. The reactor will require about 11 kg U-235 in LEU (19.9%) each year, which would correspond to a need of about 2,000 SWU per year.

Appendix. 1997 Accident

An accident in early 1997 may permit a crude check on the number of centrifuges operating at the plant in early to mid-1990s. Depleted uranium, containing 0.3-0.4 percent uranium 235, was shipped in mild steel drums from the plant to a disposal site at the Rakha Mines owned by the Uranium Corporation of India at Jakuguda in Bihar. The 1997 shipment of 56 drums had about a dozen corroded drums, and one of these drums gave way and leaked uranium.[25]

The maximum amount of enriched uranium product and the separative work units required to produce that depleted uranium can be crudely estimated. Based on information that the drums were made of mild steel and on the absence of any public mention of highly toxic fluorine, the drums are assumed to have contained uranium oxide. The drums are also assumed to have a capacity of 55 gallons, a standard-sized drum for depleted uranium not in a chemical form involving fluorine. Using nuclear industry standards, each drum is assumed to contain no more than about 175-350 kilograms of uranium, for a total of about 10-20 tonnes of uranium in all 56 drums. If only HEU had been produced, and the upper figure of 20 tonnes is used, then this amount of depleted uranium would correspond to about 80 kilograms of HEU enriched to 90 percent or 375 kilograms of HEU enriched to 20 percent.[26] Production of this amount of HEU would have required 13,400 to 14,500 SWU for the 20 and 90 percent enriched uranium, respectively, or about 14,000 SWU. If three percent enriched uranium had been produced, this amount of depleted uranium would correspond to about three tonnes of LEU and about 10,000 SWU. Because the plant likely produced mostly LEU, the latter value of 10,000 SWU is used. If only 10 tonnes were in the drums, the values would be halved to 40-190 kilograms of HEU and about 5,000 SWU.

Assuming that the operators followed standard practice and loaded the depleted uranium into non-corroded drums, many of these drums would have been likely stored for years. If the drums had been stored for five to seven years, and the drums represented the bulk of the depleted uranium produced by RMP, the total output of the RMP during this period would have been about 5,000-10,000 SWU. The estimated average annual output during these 5-7 years would have been roughly 700-2,000 SWU per year. Assuming each centrifuge had a capacity of 2-3 SWU per year, such an annual output would imply that roughly 250-1,000 subcritical centrifuges were operating during this period. Because the amount of depleted uranium in each drum could have been significantly less than posited above, these values should be viewed as upper bounds. Nonetheless, this case suggests that the RMP had not managed to operate thousands of centrifuges by 1997.

[25] Vijendra Raoj, "Leaks Reported in Steel Drums Containing Uranium," Bangalore Deccan Herald (internet version) March 14, 1997.
[26] This calculation assumes a tails assay of 0.35 percent.

Figure 1. Likely site of Rare Materials Plant, Mysore, India