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An Estimate of India's Uranium Enrichment Capacity

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Although the existence of India's uranium enrichment program has been known for a while, there is little technical information on the program available in the public domain. Here, we try to estimate its capacity based on the assumption that it has succeeded in producing sufficient enriched uranium for the core of the prototype reactor for the nuclear submarine that India has been developing. While there are large uncertainties in the data and, consequently, our estimates, this exercise is nonetheless useful to get a sense of scale and can be used to make rough estimates of how much weapons grade uranium could be produced at this facility should India use it for that purpose.

There are two uranium centrifuge enrichment facilities in India.[1] Interest in uranium enrichment dates back to the early 1970s.[2] But it was only in 1986 that Indian Atomic Energy Commission Chairman Raja Ramanna announced that uranium had successfully been enriched.[3] According to one report, a pilot scale plant has been operating in the Bhabha Atomic Research Center complex since 1985.[4] A larger centrifuge plant has been reportedly operating at Rattehalli, Karnataka, since 1990.[5] Construction of the Rattehalli plant started in the mid 1980s.[6] During the initial years of operation, the plant reportedly had "frequent

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breakdowns as a result of corrosion and failure of parts."[7] However, in 1997, it was reported that the Department of Atomic Energy (DAE) was "planning to build and install rotor assemblies of improved design."[8]

The primary purpose of the Rattehalli plant appears to be to enrich uranium for the nuclear submarine, officially termed the Advanced Technology Vessel (ATV), program. One indication of the military nature of the work carried out at Rattehalli is the transfer of the facility to the Defense Ministry shortly after the May 1998 nuclear tests.[9] It is also possible that enriched uranium from this facility was used in the hydrogen bomb tested on 11 May 1998.[10] Highly-enriched uranium is used in U.S. and Russian thermonuclear weapons.

There have been a few indications of the technical characteristics of the Rattehalli enrichment plant. According to a report from the early 1990s quoting unnamed official sources, the facility consists of "several hundred operating centrifuges made of domestically-produced maraging steel" with "a likely design throughput of under three separative work units (SWU) per machine per year."[11] One could take this to mean a total enrichment capacity of about 1000–2000 SWU/year. In 1997, it was reported that the DAE was planning to "build and install rotor assemblies of improved design." Different enrichment levels for the output of the facility and the requirement for the submarine reactor have been reported; these range from 6%–45%.

If, as Indian officials state, the primary purpose of the Rattehalli facility is to produce fuel for the ATV program, an analysis of the submarine reactor requirements could help estimate the uranium enrichment capacity.[13] Despite relatively prolific coverage of the Indian nuclear submarine program in the media, there is considerable confusion about its technical characteristics. In part this reflects the fact that the program started over 25 years ago and has evolved considerably over the decades.[14]

After numerous setbacks and failures, by the late 1990s a reactor design was finalized, and testing of a prototype commenced at the Kalpakkam nuclear complex in southern India.[15] This implies that between 1990 and the late 1990s, the Rattehalli complex should have produced at least sufficient enriched uranium to fabricate the reactor core.[16]

The amount of enriched uranium needed for a nuclear submarine reactor depends on a number of factors. These include the reactor power rating, the level of enrichment, the time intervals between core refuelings, the burn-up (which determines the fraction of the initial U-235 that is consumed before refueling [by conversion to U-236 as well as fission]), the reactor design (including factors such as fuel geometry, the use of burnable absorbers, and so on), and the use pattern (the average number of effective full power days per year or the average power the reactor produces through its lifetime). None of these are definitively known, and there are contradictory reports on some of these quantities (such as the power rating of the reactor).

One can set a lower bound on the power required by a submarine by estimating what is needed to overcome drag at the maximum design velocity. The drag power requirement for a submarine is given by:

$$P \approx 0.5 C_d \rho_w V^{2/3} u^3,$$

where C_d is the effective drag coefficient, ρ_w is the density of sea water which we will take to be 1.01 ton/m^3, u is the velocity of the submarine and V is the volume of the submarine, also called the displacement. Power is also needed for other activities on the submarine, but these requirements are smaller than the drag power requirements.

For a streamlined design, the effective drag coefficient would be about 0.025. But for a less efficient design, it may be about 0.035.[17] Since this is the first submarine hull of this size that India is building, and because its diameter must be large enough to hold the propulsion reactor, we assume that the drag coefficient has the higher value of 0.035. The maximum velocity of the ATV is usually given as about 30–35 knots, which corresponds well to maximum velocities reported for other nuclear submarines.[18] We will choose the lower value of 30 knots (15 m/s).[19]

There is considerable confusion about the displacement volume as well and reported values range from 1600 tons to 9400 tons.[20] We will choose a value of 5000 metric tons. One reason for this choice is that many of the Indian submarine characteristics are reported to be similar to the 670 series (Charlie Class) of Russian nuclear submarines.[21] India leased a Charlie I class submarine from Russia between 1988 and 1991.[22] This has a displacement of 5000 tons.[23]

For a drag coefficient of 0.035, a displacement of 5000 tons, a maximum speed of 30 knots, the propulsive power required is 25,460 shp[24] (shaft horsepower; 1 shp = 0.746 kW). A comparison of several nuclear submarines shows that typically the rated shaft horsepower is about 5% to 40% greater than the drag power requirements.[25] Assuming a figure of 20% for other power requirements, the total comes to about 30,000 shp (22.4 MW).

The thermal power rating of the reactor would have to be larger due to thermodynamic inefficiency and losses in the propeller/transmission system. Assuming an overall conversion efficiency of 20%, the reactor power needed is about 112 MWth. The minimum reactor power rating among the values cited in the literature that is consistent with these submarine propulsion requirements is 150 MWth. This power rating is similar to the reactors used in the French *Le Triomphant* nuclear submarines. However, this estimate is sensitively dependent on the assumptions made about various quantities. For example, if the drag coefficient is only 0.025, the reactor power needed is only about 80 MWth. Therefore, it may well be possible that the submarine reactor is only 90 MWth, one of the values widely cited. However, it seems unlikely that the reports that the reactor power is only 40–50 MWth are correct.

We now turn to the question of how much uranium is required for the submarine reactor core to operate at this power level. Since this would depend on the reactor design and naval reactor designs are generally kept secret, it is not easy to calculate the uranium inventory. Further, the amount of U-235 consumed each year depends on the operational procedures and patrol routines followed by the submarine. For the same power rating and time between refuelings, the uranium inventory for a submarine that has a more demanding patrol routine would be higher. Information about such matters is not available publicly.

There are, however, a few estimates of uranium requirements. Based on historical naval procurement figures in the United States, as well as details of a submarine core offered to France that were revealed at the 1959 hearings of the U.S. Joint Committee on Atomic Energy, Frank von Hippel, David Albright, and Barbara Levi estimated that the U-235 requirements for U.S. submarines are about 0.6–0.7 g/shp-year.[26] However, the United States is exceptional in the way that it uses its submarines, which routinely patrol around the entire globe. Its uranium requirements are therefore higher than might be expected for an Indian submarine.

Russian submarine reactors have less demanding routines.[27] Hence their fuel requirements are somewhat lower as in the case of the reactors mentioned earlier. A Russian second generation submarine (for example, one belonging to the Charlie class) reactor with a rating of 70–90 MW contains typically about 315 kg of 20% enriched uranium, that is, about 63 kg of U-235, in its core.[28] Another source estimates the U-235 inventory as 70 kg.[29] The propulsive power rating for Charlie Class submarines is 20,000 shp.[30] Assuming a typical 10-year lifetime for the core, the uranium requirement is 0.315–0.35 g/shp-y, about half of that of the United States.

The Sevmorput nuclear icebreaker/cargo ship uses 150.7 kg of U-235,[31] and has a propulsive power rating of 40,000 shp.[32] It therefore requires 0.375 g/shp-year of U-235 (assuming a 10-year lifetime for the core).

We assume that the ATV will require about 0.3 g/shp-year of U-235. This is about half the U-235 requirement of U.S. submarines, and a little lower than Russian submarines. The core of the ATV is reported to have a design lifetime of 10 years.[33] Therefore, the initial core for a 30,000 shp ATV requires about 90 kg of U-235.

Table 1: SWU requirements.

Enrichment	Tails	SWU/kg	Kg-EU/kg-U-235	SWU/kg-U-235	kg-feed*/kg-U-235
30	0.3	59.8	3.3	199.3	240.9
40	0.3	81.5	2.5	203.7	241.5
45	0.3	92.4	2.2	205.3	241.7
40	0.2	96.6	2.5	241.5	194.7
40	0.5	64.4	2.5	161	468

*Feed is assumed to be natural uranium.

This estimate has involved many assumptions and uncertainties in the data. Varying some of these, we estimate that the core of the ATV might use about 40–160 kg of U-235.

The SWU requirements, the feed (natural uranium) requirements, and the amounts of uranium enriched to different levels containing 1 kg of U-235 are summarized in Table 1. For a given tails enrichment level, the SWU requirement per unit mass of U-235 does not depend strongly on the enrichment level. This SWU requirement may be lowered by using a higher enrichment level for the tail, but that would significantly increase the amount of uranium used as feedstock. We therefore assume that the tails enrichment level is 0.3%, which means that that it would take approximately 200 SWU to produce a kilogram of U-235. Thus, manufacturing the 90 kg submarine core would require 18,000 kgSWU of enrichment capacity. A 40 kg core would require 8,000 kgSWU of enrichment capacity and a 160 kg core would require 32,000 kgSWU of enrichment capacity.

From media accounts, it appears that the centrifuge plant began producing significant quantities of enriched uranium in 1991. Since the testing of the reactor reportedly started around 2000 or 2001, one may assume that the enriched uranium used in the core was ready by 1999 (assigning one year to fuel fabrication and assembly). This would imply about 8 years of production, and therefore an average enrichment capacity of 2250 SWU/y. However, it is quite likely that the capacity was not a constant and that once the technology had been perfected, more centrifuges would have been added, increasing the capacity.[34] Assuming that in 1991 the capacity was 1500 SWU/year (the midpoint of the 1000–2000 SWU/y capacity mentioned earlier) and that the capacity increased linearly, an average capacity of 2250 SWU/y would imply a capacity of 3000 SWU/y in 1999. This, then, is the estimate of the enrichment capacity needed to produce the 90 kg submarine core. At the upper end, a 160 kg core would imply a capacity of 6500 SWU/y in 1999. At the lower end, even the assumed 1991 enrichment capacity of 1500 SWU/y is more than adequate to produce a 40 kg core. Hence the lower bound on the reactor core provides no real constraint on the enrichment capacity, and we will not consider it any further.

An additional demand for enriched uranium might be to test or manufacture thermonuclear weapons. In two-stage thermonuclear weapons enriched uranium can be used in the primary, in the "spark plug" to aid in initiating the fusion reaction, or in the "pusher" encasing the fusion fuel.[35] Enriched uranium may also be used to replace the "blanket" surrounding the warhead, which is usually made of depleted uranium, so as to increase the yield of a thermonuclear weapon.[36] According to one report, a "modern thermonuclear weapon may contain only a few tens of kilograms" of U-235.[37]

The rule of thumb used by the U.S. Enrichment Corporation, which is the agent for the sale of blended down weapon-grade (90% U-235) uranium recovered from excess Russian weapons, is 25 kg per warhead.[38] However, this figure may not be applicable to the Indian thermonuclear design. The bulk of enriched uranium used in U.S. and Russian thermonuclear weapons is likely to be for the blanket in order to increase the yield of the weapon or in the core itself in order to lower the volume.

According to the official announcement that followed the 1998 tests, "the yield of the thermonuclear device tested on May 11 was designed to meet stringent criteria like containment of the explosion and least possible damage to building and structures in neighbouring villages."[39] If this were indeed the case, it is likely that the blanket may have been made of inert material. The requirement for enriched uranium may only be a few kilograms used in the spark plug in this case.[40] We will assume this figure to be 5 kg and that about 10 kg of U-235 was produced for the test carried out on 11 May 1998. Apart from the amount actually used in the device exploded, this would also include processing losses and material used for conducting laboratory experiments. In this scenario, the Rattehalli plant should have produced at least 100 kg of U-235 by 1999 for the submarine core and the thermonuclear device tested on 11 March 1998. Depending on whether India decided to stockpile thermonuclear weapons, there may or may not be a continuing demand for enriched uranium for weapons.

Our estimates of enrichment capacity are listed in Table 2. The best estimate of current (2003) capacity from our analysis is 4500 SWU/y. At enrichment capacities of 3750–9750 SWU/y, the facility could produce about 20–50 kg of weapons grade uranium (90% enrichment).

One additional demand for enriched uranium might come from India's nuclear power program. However, there is no indication that India is seeking to fuel any of its Light Water Reactors with indigenous enriched uranium. This is also borne out by the above estimates of the capacity. A facility with a capacity of 3750 to 9750 SWU/year could produce 0.94 to 2.45 tons of 3.3% enriched uranium each year. This is to be compared with the initial core loading of 66 tons

Table 2: Estimates of enrichment capacity.

Requirements	**Average enrichment capacity (1991–1999)**	**Enrichment capacity in 1999***	**Current enrichment capacity (2003)***
Submarine core (90 kg U-235)	2250 SWU/y	3000 SWU/y	3750 SWU/y
Submarine core (160 kg U-235)	4000 SWU/y	6500 SWU/y	9000 SWU/y
90 kg submarine core + 1998 Thermonuclear test (10 kg U-235)	2500 SWU/y	3500 SWU/y	4500 SWU/y
160 kg submarine core + 1998 Thermonuclear test (10 kg U-235)	4250 SWU/y	7000 SWU/y	9750SWU/y

*Assuming linearly increasing capacity.

for the VVER-1000 reactors that India is importing from Russia. Thus, at the estimated range of current capacities, it would take decades for India to enrich sufficient uranium for even one reactor core.

One may compare these values for the enrichment capacity and WGU production capacity with what is known. It has generally been assumed that India's enrichment capacity is smaller than Pakistan's capacity. Since Pakistani enrichment capacity is estimated at 9000-15000 SWU/y,[42] our estimates are consistent with this assumption. Our estimates of annual HEU production capacity are larger than the "at most 10 kg/year" capacity estimated by RAND analyst Gregory Jones,[43] but consistent with the 28 kg/year cited by other sources.[44]

This estimate of enrichment capacity also has implications for the size of the nuclear submarine fleet that can be sustained. At 200 SWU/kg-U-235 and 90 kgU-235/reactor core, a 4500 SWU/y facility could produce a reactor core in about four years. Nuclear strategists have argued that India requires a fleet of three to five submarines.[45] Since each submarine would need a new core in 10 years, the estimated current capacity may be just insufficient to produce the enriched uranium requirements for a 3-submarine fleet. But since the enrichment capacity can be increased, this may not be a major bottleneck.

Details of uranium enrichment activities have been kept largely secret in India, even more so than other nuclear activities.[46] We have therefore performed these calculations in a transparent manner laying out the methodology and assumptions explicitly. This allows for the possibility that this can be corrected should better data become available.

NOTES AND REFERENCES

1. There is also an experimental laser enrichment program.

2. David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996* (New York: Oxford University Press, 1997), pp. 269–270.

3. Brahma Chellaney, "Indian Scientists Exploring U Enrichment, Advanced Technologies," *Nucleonics Week*, 5 March 1987, p. 9.

4. Ivan Fera and Kannan Srinivasan, "Keeping the Nuclear Option Open: What It Really Means," *Economic and Political Weekly*, 6 December 1986, pp. 2119–2120.

5. Mark Hibbs, "Second Indian Enrichment Facility Using Centrifuges Is Operational," *Nuclear Fuel*, 26 March 1992, p. 9.

6. Ivan Fera and Kannan Srinivasan, "Keeping the Nuclear Option Open: What It Really Means," *Economic and Political Weekly*, 6 December 1986, pp. 2119–2120.

7. David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996*, (New York: Oxford University Press, 1997), p. 270.

8. Mark Hibbs, "India to Equip Centrifuge Plant with Improved Rotor Assemblies," *Nuclear Fuel*, 1 December 1997, p. 7.

9. "BARC Secret Programme will be Transferred to the Defence Ministry," *Indian Express*, 17 May 1998.

10. Though the yield of the nuclear test and therefore the success of the design have been questioned, there is no reason to doubt official Indian assertions that a two-stage thermonuclear bomb was tested.

11. Mark Hibbs, "Second Indian Enrichment Facility Using Centrifuges Is Operational," *Nuclear Fuel*, 26 March 1992, p. 9.

12. Mark Hibbs, "India to Equip Centrifuge Plant with Improved Rotor Assemblies," *Nuclear Fuel*, 1 December 1997, pp. 7–8.

13. Strictly speaking this would only provide a lower bound. However, since the program has had operating difficulties, it is quite likely that the actual capacity is reasonably close to this lower bound.

14. For a useful history of the program see T S Gopi Rethinaraj, "ATV: All at Sea Before it Hits the Water," *Jane's Intelligence Review*, 1 June 1998, pp. 31–35.

15. Vivek Raghuvanshi, "Indian Navy Reaches Nuclear Power Milestone," *Defense News*, 5 November 2001. See also Dinesh Kumar, "India Inching Towards Indigenously Built N-powered Submarines," *The Times of India*, 3 October 1998, and A. Gopalakrishnan, "Undermining Nuclear Safety," *Frontline*, 24 June 2000. One report claims that these tests are of a "scaled down reactor" but this has not been corroborated elsewhere. Even if true, it is still likely that the Rattehalli complex would have produced sufficient enriched uranium to fabricate the entire reactor core.

16. It is of course possible that the necessary enriched uranium was produced much earlier. But the reports that the Rattehalli facility was not working well suggests that the necessary enriched uranium would have likely been produced only close to the time the reactor began to be tested.

17. Thomas Ippolito Jr., "Effects of Variation of Uranium Enrichment on Nuclear Submarine Reactor Design," Ph.D. diss., Massachusetts Institute of Technology, 1990, p. 12.

18. Vivek Raghuvanshi, "Indian Navy Reaches Nuclear Power Milestone," *Defense News*, 5 November 2001, p. 18.

19. At this speed, the ATV would take about 36 hours to go from Thiruvananthapuram, a likely site for India's strategic nuclear command center, to Karachi, Pakistan's chief port and a likely site of naval blockade by India in the event of a war.

20. The displacement is usually given in tons, corresponding to the weight of the water displaced. Since the density of water is approximately 1 ton/m^3, the displacement is roughly the same in cubic meters.

21. Dmitry Litovkin, "Indian Nuclear Submarine Fleet Development Program: Russian Participation," *YadernyKontrol (Nuclear Control) Digest*, no. 10 (Spring 1999), pp. 46–50, p. 48. An Indian defense journal claims that the ATV's "hull designs are based on the Charlie Class, drawings of which were obtained from Russia but India is developing its own reactor for the boat." http://www.indiadefence.com/ATV.htm (25 March 2004).

22. Andrew Koch, "Nuclear-powered Submarines: India's Strategic Trump Card," *Jane's Intelligence Review*, 1 June 1998, pp. 29–31.

23. Federation of American Scientists, Washington, D.C., Russia Soviet Nuclear Forces Guide, Project 670 Skat / Charlie I, Project 670M Skat-M/Charlie II, http://www.fas.org/nuke/guide/russia/theater/670.htm (25 March 2004).

24. A measure of the actual mechanical energy per unit time delivered to a turning shaft.

25. This calculation is based on numbers in Chunyan Ma and Frank von Hippel, "Ending the Production of Highly Enriched Uranium for Naval Reactors," *The Nonproliferation Review* (Spring 2001), pp. 86–101, p. 91.

26. Frank von Hippel, David H. Albright, and Barbara G. Levi, *Quantities of Fissile Materials in US and Soviet Nuclear Weapons Arsenals*, Princeton University/Center for Energy and Environmental Studies Report No. 168 (July 1986), pp II-2 – II-5. It is worth emphasizing that this estimate is related to the use-pattern of U.S. nuclear submarines—the number of effective full power days/year.

27. See for example Pavel Podvig, ed., *Russian Strategic Nuclear Forces* (Cambridge, MA: The MIT Press, 2001), pp. 273–278.

28. Oleg Bukharin, "Analysis of the Size and Quality of Uranium Inventories in Russia," *Science and Global Security* 6 (1996), pp. 59–77.

29. Thomas Nilsen, Igor Kudrik, and Alexandr Nikitin, "The Russian Northern Fleet: Nuclear Powered Vessels," Bellona Report nr. 2:96 http://www.spb.org.ru/bellona/ehome/russia/nfl/nfl2-1.htm#O15 (25 March 2004).

30. Federation of American Scientists, Washington, D.C., Russia Soviet Nuclear Forces Guide, Project 670 Skat / Charlie I, Project 670M Skat-M /Charlie II, http://www.fas.org/nuke/guide/russia/theater/670.htm (25 March 2004).

31. Morten Bremer Maerli et al., *Criticality Considerations on Russian Ship Reactors and Spent Nuclear Fuel* (Oslo: Norwegian Radiation Protection Authority, 1998).

32. Povl L. Ølgaard, "The Potential Risks from Russian Nuclear Ships," available on the internet at http://www.svanhovd.no/nrpa/nks/paperpovl.pdf (25 March 2004).

33. "Reactor for N-submarine by Next Year," *The Hindu*, 17 August 1999.

34. There would, of course, be some reduction in these numbers from failure of centrifuges due to aging and other causes, but it could be expected that the production capacity of centrifuges will be increased to account for these losses.

35. See for example Chuck Hansen, *The Swords of Armageddon: US Nuclear Weapons Development since 1945*," CD-ROM, (Chuck Hansen, 1995), p. 1–94. The spark plug is a fissile mass placed in the center of the fusion fuel. When the fusion fuel is compressed by the shock wave, the fissile mass is compressed to supercritical densities setting off a chain reaction, which increases the yield and produces additional neutrons that could induce ignition of the secondary.

36. Robert Alvarez and Debra Sherman, "U.S. to Resume Uranium Production for Weapons," *Bulletin of the Atomic Scientists* (April 1985), pp. 28–30, p. 29.

37. Chuck Hansen, *The Swords of Armageddon: US Nuclear Weapons Development since 1945*," CR-ROM, (Chuck Hansen, 1995), p. 1–94.

38. USEC, Inc., US-Russian Megatons To Megawatts Program, *Recycling Nuclear Warheads into Electricity,* http://www.usec.com/v200102/HTML/MegatonsFAQ.asp (25 March 2004).

39. "Joint Statement by Department of Atomic Energy and Defence Research and Development Organisation," New Delhi, 17 May 1998. Available on the internet at http://www.indianembassy.org/pic/PR1998/May98/prmay1798.htm (25 March 2004).

40. This would presumably increase the chances of igniting the secondary, a likely goal for a first thermonuclear test.

41. Nuclear Engineering International, *World Nuclear Industry Handbook* (Sutton, England: Business Press International, 1998), p. 60.

42. David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities and Policies* (Oxford: Oxford University, 1997), p. 275.

43. Gregory Jones, "From Testing to Deploying Nuclear Forces," RAND Report IP-192 (2000); available on the internet at http://www.rand.org/publications/IP/IP192/ (25 March 2004).

44. See for example, Nicholas, Berry, Building the Indian Bomb, Center for Defense Information, Washington, D.C., http://www.cdi.org/ISSUES/TESTING/inbombfct.html (25 March 2004).

45. See the discussion on pp. 380–381 in C. Rammanohar Reddy, "Nuclear Weapons Versus Schools for Children: An Estimate of the Cost of the Indian Nuclear Weapons Programme," in M. V. Ramana and C. Rammanohar Reddy, eds., *Prisoners of the Nuclear Dream* (New Delhi: Orient Longman, 2003), pp. 360–408.

46. For example, the Rattehalli site was not included in the list of nuclear sites exchanged by the governments of India and Pakistan as a confidence building measure. Mark Hibbs, "India and Pakistan Fail to Include New Swu Plants on Exchanged Lists," *Nuclear Fuel*, 30 March 1992, p. 6.