CHAPTER 4

PLUTONIUM PRODUCTION IN INDIA AND THE U.S.-INDIA NUCLEAR DEAL

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INTRODUCTION

On July 18, 2005, U.S. President George W. Bush and Indian Prime Minister Manmohan Singh issued a joint statement in Washington, DC, laying the grounds for the resumption of U.S. and international nuclear trade with India.[1] This trade has been restricted for about 3 decades because India is neither a signatory to the nuclear nonproliferation treaty nor allows International Atomic Energy Agency (IAEA) safeguards on all its nuclear facilities. The July agreement has generated political debate in the United States and India, and concern on the part of a number of other countries.[2] Among the issues is the fear that the agreement serves to normalize India's status as a nuclear weapons state and so weakens the Nuclear Non-Proliferation Treaty (NPT) and the larger nonproliferation regime. An important concern is that it may serve to expand India's potential nuclear weapons production capabilities and thus hinder international efforts to end the production of fissile materials for nuclear weapons.

The United States has started to amend its own laws and policies on nuclear technology transfer and to seek the necessary changes in the international controls on the supply of nuclear fuel and technology managed by the Nuclear Suppliers Group (NSG) of states so as to allow nuclear trade with India. In exchange for the lifting of these restrictions, India's government has identified several nuclear facilities that it will designate as civilian and will volunteer for IAEA safeguarding. Currently, India has four power reactors under IAEA safeguards, the U.S.-built Tarapur 1 and 2, and the Canadian-built Rajasthan 1 and 2. The two Koodankulam reactors that are under construction by Russia also will be subject to safeguards.

India has proposed that it will place eight additional reactors under safeguards between 2006 and 2014, each with a capacity of 220 MWe (see Appendix I). These reactors are:[3]

- Two Rajasthan reactors still under construction, RAPS 5 and 6, which would be made available for IAEA monitoring when they commence operation in 2007 and 2008 respectively,
- RAPS 3 and 4, which are already operating but would only be available for safeguards in 2010,
- The two Kakrapar reactors, which would be made available for safeguards in 2012, and

- The two reactors at Narora which would become available for safeguards in 2014.

Some of the facilities at the Nuclear Fuel Complex, Hyderabad, also have been identified as civilian and are to be offered for safeguards by 2008.[4] Other facilities to be declared civilian include three heavy water plants (leaving at least two out of safeguards), and the two Away-from-Reactor spent fuel storage facilities that contain spent fuel from the safeguarded Tarapur and Rajasthan reactors.

India would shut down the Canadian-build CIRUS reactor permanently in 2010 and also would shift the spent fuel from the APSARA reactor to a site outside the Bhabha Atomic Research Centre and make it available for safeguarding in 2010.

A significant proportion of India's nuclear complex would remain outside IAEA safeguards and continue to have a "strategic" function (see Appendix I). This military nuclear complex would include the Tarapur 3 and 4 reactors, each of 540 MWe capacity, the Madras 1 and 2 reactors, and the four power reactors at Kaiga.[5] Together, these unsafeguarded reactors have 2,350 MWe of electricity generation capacity. India also will not accept safeguards on the Prototype Fast Breeder Reactor (PFBR) and the Fast Breeder Test Reactor (FBTR), both located at Kalpakkam. Facilities associated with the nuclear submarine propulsion program would not be offered for safeguards. Reprocessing and enrichment facilities also are to remain outside safeguards.[6] Finally, under the deal, India retains the right to determine which future nuclear facilities it builds would be civilian and open to safeguards and which would not.

At the March 2006 summit in New Delhi between President Bush and Prime Minister Singh, it was announced that the U.S. Government was satisfied with this proposed Indian plan to separate its program into a civilian and a military component.[7] However, the final shape and status of the deal still is unclear since the U.S. Congress has not agreed on amendments to existing laws and may attach conditions that India may not accept. There also needs to be a consensus among the NSG countries in support of making an exemption to its rules for India.[8]

Technical issues related to fissile materials that are involved in these concerns about the agreement are discussed below.[9] First India's current plutonium production and stockpiles are estimated. The significance for India's future weapons-useable plutonium production capabilities of the line India has drawn between its civilian and military facilities are then assessed.

INDIA'S NUCLEAR PROGRAM

Established in 1948, India's Atomic Energy Commission turned to the United Kingdom (UK) for the design and enriched uranium fuel for its first nuclear reactor, Apsara. Similarly, the CIRUS reactor was supplied by Canada, while the heavy water used in it came from the United States. India's first power reactors at Tarapur and Rawatbhata were supplied by the United States and Canada respectively. A U.S. design was used for its first reprocessing plant in Trombay. Some of these technologies and materials contributed to the production and separation of the plutonium used in India's 1974 nuclear weapons test. Due to this test and the subsequent refusal to give up its nuclear weapons and sign the nuclear nonproliferation treaty (NPT), India has been kept largely outside the system of trade of nuclear technology that has developed over the past 3 decades.

India over the years has built a nuclear power program, with 15 reactors [Appendix I] providing an installed capacity of 3,310 megawatts electric (MWe), which accounts for about 3 percent of India's installed electricity generation capacity. Thirteen of the reactors are Pressurized Heavy Water Reactors (PHWRs), the first two of which were supplied by Canada. The other PHWR reactors are based largely on the Canadian design. The latest evolution of the design has increased the capacity from 220 to 540 MWe. The other two power reactors are Boiling Water Reactors supplied by the United States.

Only the four foreign supplied reactors currently are under IAEA safeguards. Two 1,000 MWe reactors being built by Russia under a 1988 deal also will be safeguarded. These two large reactors will increase India's nuclear capacity by over 50 percent in the next few years. Figure 1 shows the development of India's safeguarded and unsafeguarded nuclear capacity and how it will evolve in the coming years, including the effects of the U.S.-India nuclear deal.

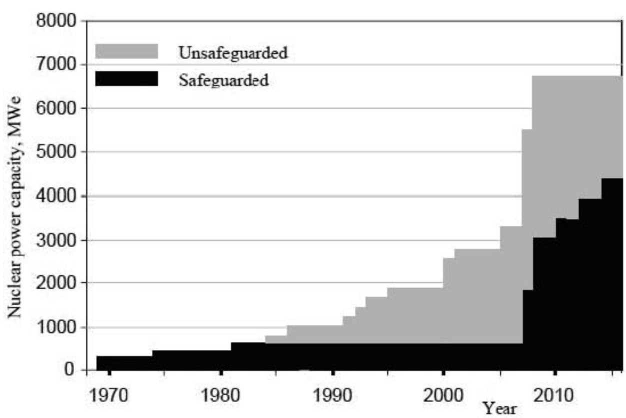

Figure 1. The Evolution of India's Installed Nuclear Electricity Generation Capacity.

For decades, India's Department of Atomic Energy (DAE) has pursued an ambitious fast-breeder reactor development program. This involves separating plutonium from the spent fuel produced in natural uranium reactors and using it to fuel fast-neutron breeder reactors, which in turn could be used to produce U-233 that eventually would serve to fuel breeder reactors operating on a Th-U-233 closed fuel cycle.[10] These efforts have made halting progress: The first breeder reactor to be built, the Fast Breeder Test Reactor, was due to become operational in 1976 but started only in 1985 and has been plagued with problems.[11] The 500 MWe Prototype Fast Breeder Reactor is not expected to be completed until 2010, if all goes according to plan. India also has begun work on a prototype plutonium-thorium-uranium-233 fuelled Advanced Heavy Water Reactor (AHWR) to gain experience with the thorium and uranium-233 fuel cycle.[12]

India conducted its first nuclear weapons test in May 1974. There were another five tests in 1998, involving fission weapons and a thermonuclear weapon. There are reports that at least one test used plutonium that was less than weapons grade.[13] India is believed to have a stockpile of perhaps 40-50 nuclear weapons, and one report cites plans for 300-400 weapons within a decade.[14]

FISSILE MATERIALS IN INDIA

India is producing plutonium for its nuclear-weapons programs. Along with Israel, Pakistan, and perhaps North Korea, it may be the only state currently doing so. The five NPT nuclear weapons states, United States, Russia, UK, France, and (informally) China, have all announced an end to fissile material production for weapons. India also is reprocessing the spent fuel from its nuclear power reactors, an option pursued currently only by Russia, France, and the UK. Japan is about to begin operating a large reprocessing plant. Other countries simply store their spent nuclear fuel.

Weapons Grade Plutonium.

India's weapons grade plutonium comes from the 40 megawatt thermal (MWt) CIRUS and 100 MWt Dhruva reactors. Assuming that the reactors operate at full power when they are available allows an upper-bound estimate of plutonium production. At full power and an availability factor of 70 percent, each year CIRUS would produce about 9.2 kg of weapons grade plutonium, and Dhruva would produce about 23 kg of weapons grade plutonium.[15] The estimated cumulative weapons grade plutonium produced by 2006 CIRUS is 234 kg and by Dhruva about 414 kg.[16]

Spent fuel from CIRUS and Dhruva is reprocessed at the Trombay reprocessing plant (with a capacity of about 50 tons of spent fuel per year). It is hard to know how much of the plutonium that has been recovered from spent fuel has been incorporated into weapons.

It is estimated that over the years a total of 131 kg of India's weapons grade plutonium has been consumed in nuclear weapons tests, as reactor fuel and in processing losses. This would leave India with a current stockpile of about 500 kg of weapons grade plutonium.[17] It is typically assumed that 5 kg of plutonium is sufficient for a simple nuclear weapon. (More advanced designs could use as little as 3 kg). Thus, India's current stockpile of weapons grade plutonium would be equivalent to about 100 nuclear weapons. It is not known how much of this has been fabricated into weapons components.

Civil Plutonium.

Power reactors produce plutonium in their fuel as a normal byproduct of energy generation. As of May 2006, India's unsafeguarded reactors had produced about 149 terrawatt hours (TWh) of electricity. Their accumulated spent fuel produced so far would contain about 11.5 tons of plutonium.[18] They are now producing about 1.45 tons of plutonium per year. The currently safeguarded power reactors have produced a total of 108 TWh of electricity, and 1266 tons of spent fuel, containing about 6.8 tons of plutonium.[19]

In India, the chosen way of dealing with the spent nuclear fuel from power reactors is through reprocessing. India has two large reprocessing plants at Tarapur (about 100 tons/year) and Kalpakkam (about 100 tons/year) to recover plutonium from spent power reactor fuel.[20] It plans to increase its annual reprocessing capacity to 850 tons by 2014 to meet the needs of its fast breeder reactor program and AHWR.[21]

The "reactor-grade" plutonium in the high burnup spent fuel being discharged by these reactors has a different mix of isotopes from weapons grade plutonium. However, reactor grade plutonium can be used to make a nuclear explosive and, as mentioned earlier, one of India's May 1998 nuclear tests is reported to have involved such material. In his history of the Indian nuclear weapons program, George Perkovich claims "knowledgeable Indian sources confirmed" use of nonweapons grade plutonium in one of the 1998 tests, while Raj Chengappa in a semi-official history of 1998 tests claims "one of the devices . . . used reactor grade or dirty plutonium."[22] An estimated 8 kg of such reactor grade plutonium would be required to make a simple nuclear weapon.[23]

Figure 2 summarizes these estimates for the different stockpiles of plutonium that India has accumulated so far. However, the exact amount of separated plutonium that India has produced so far is not known.

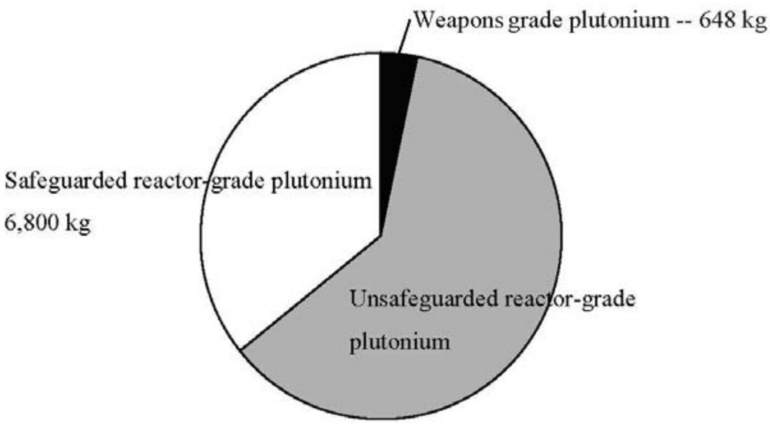

Figure 2. India's Total Plutonium Production.

The Uranium Constraint.

One important reason for the DAE's willingness to agree to have more of its nuclear facilities placed under safeguards is India's severe and growing shortage of domestic uranium. An Indian official told the BBC soon after the U.S.-India deal was announced, "The truth is, we were desperate. We have nuclear fuel to last only till the end of 2006. If this agreement had not come through we might have as well closed down our nuclear reactors and by extension our nuclear program."[24] The former head of the Atomic Energy Regulatory Board has reported that "uranium shortage" has been "a major problem . . . for some time."[25]

Nuclear Power Corporation of India Limited (NPCIL) data shows that most of its reactors have had lower capacity factors in the last few years.[26] Figure 3 shows the recent trend in operating capacity factors at India's nuclear power reactors as reported by NPCIL. It does not include data for Narora-1 and Rajasthan-1, both of which were shut-down for part of this period. The Indian Planning Commission noted that these reduced load factors were "primarily due to nonavailability of nuclear fuel because the development of domestic mines has not kept pace with addition of generating capacity."[27]

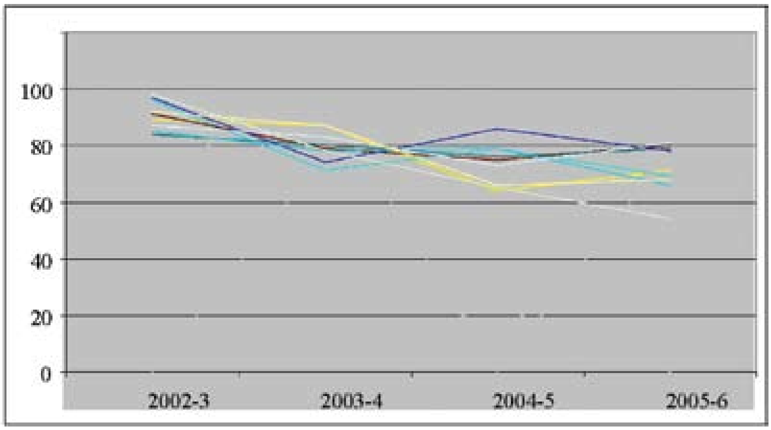

Figure 3. The Recent Decline in Indian Nuclear Power Plant Capacity Factors.

As of May 2006, the total electric capacity of India's power reactors that were domestically fuelled was 2,990 MWe—this includes the Rajasthan 1 and 2 reactors, which are under safeguards but have to be fuelled by domestic uranium. At 80 percent capacity, all these reactors would require about 430 tons of natural uranium fuel per year. The weapons grade plutonium production reactors, CIRUS and Dhruva, consume about another 35 tons of uranium annually. The uranium enrichment facility would require about 10 tons of natural uranium feed a year. Thus, it is estimated that the total current requirements are about 475 tons of domestic natural uranium per year. Nuclear Fuel Complex Chairman R. Kalidas has said that India's current annual uranium requirement is on the order of 400-500 tons of uranium oxide.[28]

Figure 4 shows the different demands for domestic uranium in India. At various times, India has been able to import limited amounts of low enriched fuel for its Tarapur reactors, from the United States (which provided the reactors), Russia, France, and China.

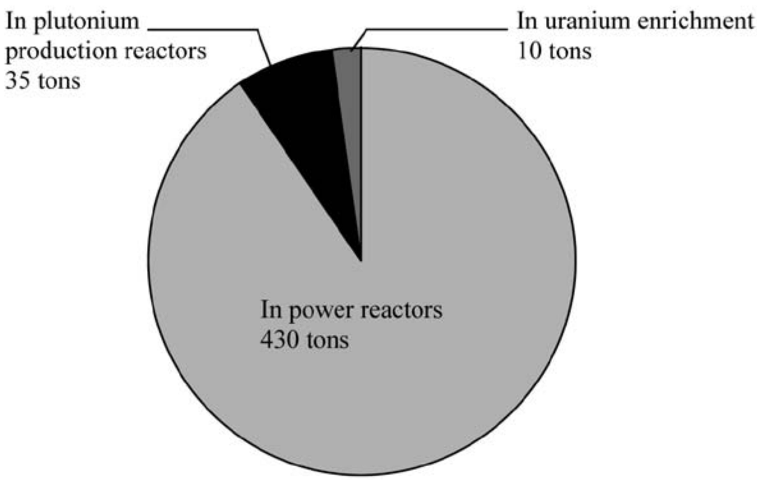

Figure 4. Annual Consumption of Domestic Uranium in India.

In comparison, it is estimated that current uranium production within India is less than 300 tons of uranium a year, well short of these requirements. It is assumed that India mines and mills 2000 tons of uranium ore per day, 300 days per year, at an average ore grade of 0.05 percent uranium. The actual ore grade being mined may be only 0.03 percent, since the better quality ore already has been used. The Jaduguda mill has a processing capacity of about 2,100 tons ore/day and may only have been producing 230 tons per year.[29] But efforts are being made to expand uranium production. An official report notes that one mill is under construction at Banduhurang, Jharkhand, and was expected to be completed in mid-2006, and that work is underway on another at Turamdih, which will have a capacity of 3,000 tons per day of ore (about 450 tons/year of uranium).[30]

DAE has been able to continue to operate its reactors by using uranium stockpiled from the period when India's nuclear generating capacity was much smaller. Estimates are that, in the absence of cut backs in India's nuclear power generation or uranium imports, this stockpile will be exhausted by 2007.

India is estimated to have total conventional uranium resources of about 95,500 tons of uranium, sufficient to supply about 10 GWe installed capacity of PHWRs for 40 years or so.[31] However, the DAE's efforts to open new uranium mines in the country have met with stiff resistance, primarily because of concerns in the communities around existing mines about the health impacts of uranium mining and milling.[32] State governments in Andhra Pradesh and Meghalaya, where DAE has found significant uranium deposits, have yet to approve new licenses for uranium mining and milling activities.[33]

It is possible, however, that DAE may be able to overcome this resistance. The most likely new sites are in the districts of Nalgonda and Kadapa, in Andhra Pradesh, with respective potential capacities of about 150-200 tons and 250 tons of uranium a year.[34] If these mines are developed, then India could meet its current domestic uranium needs for both its nuclear power reactors and weapons program. In the meantime, old mines are being reopened and existing mines expanded, including at Jaduguda.[35]

In the next few years, the domestic uranium demand for India's unsafeguarded reactors will increase further by about 140 tons/year, to 575 tons per year, as the 540 MWe Tarapur-3 and the 220 MWe Kaiga-3 and Kaiga-4 reactors are completed and begin operation in 2007. However, the total domestic uranium requirement will begin to decrease as some of the currently unsafeguarded reactors are opened for inspection in 2010, 2012, and 2014 and can thus be fueled with imported uranium along with the Rajasthan-1 and 2 reactors (see Figure 5). Consequently, if India is able to meet the additional demand for domestic uranium until 2010, the availability of uranium imports allowed by the U.S.-India deal thereafter will give it a growing excess uranium production capacity that could be used for weapons purpose.

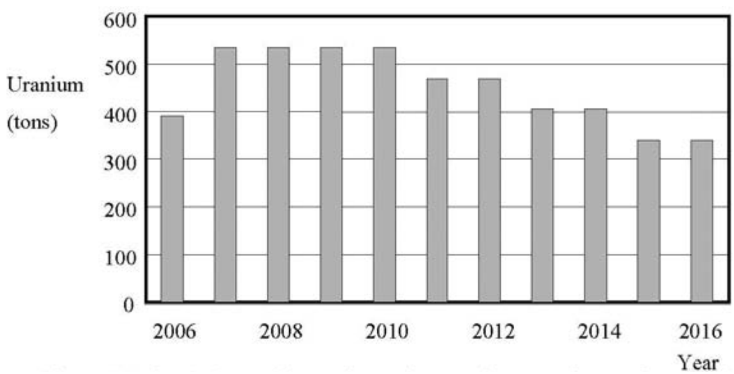

Figure 5. Estimated Annual Domestic Uranium Requirements for Unsafeguarded Heavy Water Power Reactors.[36]

India has offered to put 1,760 MWe of PHWRs under safeguards (including two reactors under construction) in addition to the two Rajasthan PHWRs with a combined capacity of 300 MWe that are already under safeguards. Without access to international uranium, all these reactors would have to be fueled using domestic uranium. At an 80 percent capacity factor, they would require about 300 tons of uranium annually.

If the deal goes through, the DAE will be able to purchase these 300 tons of uranium from the international market, in effect freeing up the equivalent of India's entire current uranium production for possible use in military facilities. With Nalgonda on line, the uranium available for the unsafeguarded power and weapons grade plutonium production reactors and the enrichment program increases to 450-500 tons/year. This would yield a uranium surplus of 75-125 tons a year after 2014.

There are several ways in which India could use its freed-up domestic uranium. In particular, concern has been raised about the possibility that it might be diverted to use in the weapons program. This option has been suggested by, among others, K. Subrahmanyam, former head of the National Security Advisory Board, who has argued that:

> Given India's uranium ore crunch and the need to build up our minimum credible nuclear deterrent arsenal as fast as possible, it is to India's advantage to categorize as many power reactors as possible as civilian ones to be refueled by imported uranium and conserve our native uranium fuel for weapons grade plutonium production.[37]

There are different ways in which this could be accomplished. One is that India could choose to build a third reactor dedicated to making plutonium for its nuclear weapons. There have been proposals for many years to build another large plutonium production reactor at the Bhabha Atomic Research Centre in Bombay.[38] The proposed reactor would be similar to the 100 MWt Dhruva that has been operating at BARC since 1985. A decision on whether to go ahead is expected early in 2007.[39] If a reactor of the same power rating as Dhruva is built, it could yield an additional 20-30 kg of plutonium, i.e., several bombs worth, each year.

India also could choose to use some of its domestic uranium to make weapons grade plutonium in one of its unsafeguarded PHWRs. This can be done by running the reactor in a "production" mode, i.e., by limiting the time the fuel is irradiated, through faster refueling.[40] This is beyond the normal design requirement of PHWR refueling machines but might be possible.

Assuming such high refueling rates are sustainable, then a typical 220 MWe pressurized heavy water reactor could produce between 150-200 kg/year of weapons grade plutonium when operated at 60-80 percent capacity.[41] Even one such reactor, if run on a production mode, could increase the existing rate of plutonium production by a factor of six to eight.[42] The net penalty for running one 220 MWe reactor in production mode is 190 tons of natural uranium.[43]

To offset this additional requirement of 190 tons/year of uranium if India were to operate a single 220 MWe PHWR in weapons grade plutonium production mode, it could recycle some of the depleted uranium recovered from the spent fuel from this reactor into the other seven unsafeguarded power reactors. This scheme involves fuelling 25 percent of the core with depleted uranium (containing 0.61 percent U-235) and ends up saving 20 percent of the normal natural uranium requirement, with the average burn up reduced to 5400 MWd/tHM.[44]

The resulting 20 percent savings on the roughly 306 tons/year of natural uranium the seven power reactors require is equivalent to 61 tons/year of natural uranium. The net penalty of running one reactor in production mode is reduced from 190 tons/year to about 130/tons per year. This implies that India could operate an unsafeguarded 220 MWe heavy water reactor in production mode, provided the Nalgonda and other mines can yield an additional 200 tons/year of uranium, and that India has sufficient reprocessing capacity to maintain the necessary flow of depleted uranium.

India already has fuelled some PHWRs using natural uranium and depleted uranium recovered as a byproduct of weapons grade plutonium production—including the Rajasthan-3 and 4, Kaiga-2 and Madras-2 reactors.[45] It has used depleted uranium recovered from low burn-up fuel from CIRUS and Dhruva.[46] These reactors generate only about 30 tons/year of spent fuel. However, there is a stock of about 750 tons of such spent fuel.[47] This would suffice for roughly 4 to 5 years if all the power reactors ran on a mixed natural and depleted uranium core.

Power Reactor Spent Fuel.

The nuclear deal does not constrain India's use of the 11.5 tons of plutonium from the spent fuel discharged by any of its currently unsafeguarded reactors. Each of the six currently operating reactors to be placed under safeguards, operating at 80 percent capacity, will add about 120 kg/year of plutonium during its remaining unsafeguarded operation. The total contribution from these six reactors will be about 4,300 kg before they are all finally under safeguards

India's total annual unsafeguarded plutonium production will increase from the current 1,450 kg/year as reactors under construction come into operation next year. It will decline in coming years as reactors are opened for inspection. Plutonium production will fall from about 2,000 kg/year in 2007 to about 1,250kg/year after 2014, when it will stabilize (see Figure 6) unless additional unsafeguarded reactors are built. Thus, the separation plan will serve to reduce India's annual production of unsafeguarded plutonium by about one-third.

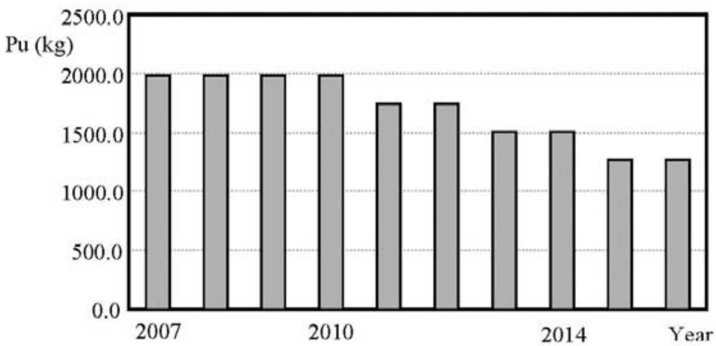

Figure 6. Annual Production of Unsafeguarded Plutonium from All Indian Power Reactors from 2007 until 2016, as Reactors Are Progressively Placed under Safeguards.

The Fast Breeder Reactor Program.

India's first large breeder reactor, the 500 MWe, Prototype Fast Breeder Reactor (PFBR) is under construction at Kalpakkam, near Madras. It is part of a larger complex that includes the Madras PHWR reactors and a reprocessing plant. This entire complex is being kept outside safeguards.[48] DAE chairman Anil Kakodkar has declared that “Both from the point of view of maintaining long term energy security and for maintaining the minimum credible deterrent the Fast Breeder Programme just cannot be put on the civilian list.”[49] This suggests that the breeder may be used to produce weapons grade plutonium. The PFBR is expected to be completed in 2010.

Fueled initially by reactor grade plutonium separated from PHWR spent fuel, the PFBR would produce weapons grade plutonium in both its radial and axial blankets of depleted uranium while the plutonium recovered from the core could be recycled for use again as fuel (Figure 7). To recover the weapons grade plutonium, the core and blanket fuel assemblies would have to be reprocessed separately. There will be a dedicated reprocessing plant specially for the FBR.[50]

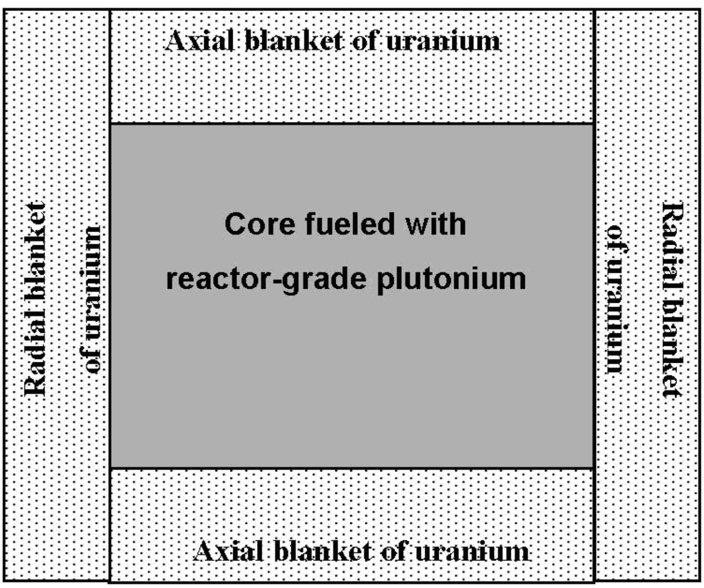

Figure 7. The Prototype Fast Breeder Reactor Burns Reactor-Grade Plutonium in Its Core and Produces Weapons-grade Plutonium in Its Radial and Axial Blankets.

The PFBR is designed to have a thermal power of 1,250 MW and an initial inventory of 1910 kg of plutonium in its core.[51] It is estimated that at 80 percent capacity the PFBR could produce on the order of 135 kg of weapons grade plutonium every year in its blanket.[52] This would amount to about 25-30 weapons worth of plutonium a year, a four- to five-fold increase over India's current weapons plutonium production capacity.

India plans to build four additional breeder reactors by 2020, and then move to larger 1,000 MWe breeders and eventually install 500 GWe of breeder capacity.[53] Each of the four planned 500 MWe breeder reactors would need two initial cores before they would be able to begin recycling their own plutonium, a total of about 16 tons.[54] India would appear to have more than sufficient unsafeguarded plutonium for placing all four of the planned breeders in the military sector. If these five breeders are built and all are kept military, then in about 15 years, India would be able to produce about 500-800 kg per year of weapons grade plutonium from them.

CONCLUSIONS

We have assessed plutonium production capabilities in India and how they might change as a result of the U.S.-India deal. India's current stockpile of weapons grade plutonium from its CIRUS and Dhruva reactors is found it to be about 500 kg. Assuming a typical figure of 5 kg of plutonium for each nuclear warhead, this stockpile would be sufficient for roughly 100 weapons. Under the deal, India will be able to produce another 45 kg of weapons grade plutonium from its CIRUS reactor before it is shut down in 2010. The Dhruva reactor will continue to operate and add about 20-25 kg/year. A second Dhruva sized reactor that is being considered would add a similar amount each year.

The most important potential increase in India's weapons grade plutonium production will come from its unsafeguarded fast breeder reactor, the PFBR, to be completed in 2010. We have estimated that it could produce about 130 kg of weapons grade plutonium each year, a four-fold increase in India's current production capability. However, the breeder would have remained unsafeguarded and produced the same amount of plutonium even in the absence of the U.S.-India deal.

India has a stockpile of about 11 tons of unsafeguarded reactor-grade plutonium. This stockpile is currently increasing at about two tons/year. We have estimated that the reactors India has offered to be safeguarded by 2014, in a phased manner as part of the deal, will contribute in total another four tons of unsafeguarded plutonium before they are opened for inspection. The eight reactors that are designated as military and will remain unsafeguarded will contribute 1,250 kg of reactor grade plutonium per year. All this reactor grade plutonium is also potentially weapons-useable.

We find that India's current domestic production of natural uranium of about 300 tons/year is insufficient to fuel its unsafeguarded reactors and sustain its current weapons grade plutonium and enriched uranium production, which altogether require about 475 tons a year. India has been able to escape this constraint so far by using stocks of previously mined and processed uranium.

Because of access to Uranium imports allowed by the deal, India may be able to produce 60-100 kg/year of weapons grade plutonium by partially running one of its unsafeguarded power reactors at low burn up. This will require operating the reactor refueling machines at much higher rates than normal and may limit the extent to which this is possible. A key constraint on this is the recycling of low-burn-up depleted uranium (containing about 0.6 percent Uranium-23 percent) as fuel. This in turn will depend on the operating capacity of India's reprocessing plants.

India already has achieved the fissile material requirements for a "minimal" arsenal, and it has been argued for some time that it should end production of fissile material for weapons.[55] It has been shown that half a dozen modest Hiroshima-yield weapons if dropped on major cities in South Asia could kill over a million people.[56] This suggests that several dozen weapons would more than suffice to meet any reasonable criteria for "minimum deterrence."[57] This number would permit a nuclear attack with a dozen warheads and provide for sufficient redundancy to deal with any concerns about survivability, reliability, and interception.[58]

Rather than pursue the option of a large expansion of its nuclear arsenal, India could choose to suspend all further production of fissile materials for weapons purposes pending the negotiation and entry into force of a Fissile Material Cutoff Treaty. This also is a necessary step in progress towards nuclear disarmament.

APPENDIX I

POWER REACTORS IN INDIA AND PAKISTAN

India (note: military reactors will not be open for safeguards)

Power reactor	Type	Power (MWe)	Start-up date	Safeguards (June 2006)	Open for Safeguards
Kaiga-1	HWR	220	16-Nov-00	Unsafeguarded	Military
Kaiga-2	HWR	220	16-Mar-00	Unsafeguarded	Military
Kakrapar-1	HWR	220	6-May-93	Unsafeguarded	2012
Kakrapar-2	HWR	220	1-Sep-95	Unsafeguarded	2012
Madras-1	HWR	170	27-Jan-84	Unsafeguarded	Military
Madras-2	HWR	220	21-Mar-86	Unsafeguarded	Military
Narora-1	HWR	220	1-Jan-91	Unsafeguarded	2014
Narora-2	HWR	220	1-Jul-92	Unsafeguarded	2014
Rajasthan-1	HWR	100	16-Dec-73	Safeguarded	Safeguarded
Rajasthan-2	HWR	200	1-Apr-81	Safeguarded	Safeguarded
Rajasthan-3	HWR	220	1-Jun-00	Unsafeguarded	2010
Rajasthan-4	HWR	220	23-Dec-00	Unsafeguarded	2010
Tarapur-1	BWR	160	28-Oct-69	Safeguarded	Safeguarded
Tarapur-2	BWR	160	28-Oct-69	Safeguarded	Safeguarded
Tarapur-4	HWR	540	12-Sep-05	Unsafeguarded	Military
Under Construction					
Kaiga-3	HWR	220	2007 (planned)	Unsafeguarded	Military
Kaiga-4	HWR	220	2007 (planned)	Unsafeguarded	Military
Kudankulam-1	VVER*	1000	2007 (planned)	Safeguarded	Safeguarded
Kudankulam-2	VVER	1000	2008 (planned)	Safeguarded	Safeguarded
Rajasthan-5	HWR	220	2007 (planned)	Unsafeguarded	2007
Rajasthan-6	HWR	220	2008 (planned)	Unsafeguarded	2008
Tarapur-3	HWR	540	2007 (planned)	Unsafeguarded	Military

*Russian: Pressurized Water Reactor.

ENDNOTES - CHAPTER 4

1. The U.S.-India nuclear agreement is at *www.whitehouse.gov/news/releases/2005/07/20050718-6.html*.

2. The politics and broader policy issues of the deal are discussed in Zia Mian and M. V. Ramana, "Wrong Ends, Means and Needs: Behind the U.S. Nuclear Deal with India," *Arms Control Today*, January/February 2006, *www.armscontrol.org/act/2006_01-02/JANFEB-IndiaFeature.asp*.

3. *Implementation of the India-United States Joint Statement of July 18, 2005: India's Separation Plan*, *mea.gov.in/treatiesagreement/2006/11ta1105200601.pdf*.

4. Fuel cycle facilities to be safeguarded are Uranium Oxide Plant (Block A), Ceramic Fuel Fabrication Plant (Palletizing) (Block A), Ceramic Fuel Fabrication Plant (Assembly) (Block A), Enriched Uranium Oxide Plant, Enriched Fuel Fabrication Plant, and Gadolinia Facility. There seem to be other fuel production facilities at the Nuclear Fuel Complex that will remain unsafeguarded, such as the New Uranium Oxide Fuel Plant; *www.aerb.gov.in/t/annrpt/anr99/srnp.htm*, and T. S. Subramanian, "Fuelling Power," *Frontline*, March 16-29, 2002, *www.frontlineonnet.com/fl1906/19060840.htm*.

5. *Implementation of the India-United States Joint Statement of July 18, 2005: India's Separation Plan*, *mea.gov.in/treatiesagreement/2006/11ta1105200601.pdf*.

6. The PREFRE reprocessing plant has had safeguards in place when running spent fuel from Rajasthan 1 and 2.

7. President Bush and Prime Minister Singh Press Conference, New Delhi, March 2, 2006, *www.whitehouse.gov/news/releases/2006/03/20060302-9.html*.

8. The Nuclear Suppliers Group member states are Argentina, Australia, Austria, Belarus, Belgium, Brazil, Bulgaria, Canada, China, Cyprus, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Kazakhstan, Latvia, Lithuania, Luxembourg, Malta, Holland, New Zealand, Norway, Poland, Portugal, South Korea, Romania, Russia, Slovakia, Slovenia, South Africa, Spain, Sweden, Switzerland, Turkey, Ukraine, United Kingdom, and the United States, *www.nuclearsuppliersgroup.org*.

9. Some of these issues are also discussed in a recent report by Ashley Tellis, *Atoms for War*, Carnegie Endowment, 2006, *www.carnegieendowment.org/files/atomsforwarrevised1.pdf*.

10. R. Chidambaram and C. Ganguly, "Plutonium and Thorium in the Indian Nuclear Programme," *Current Science*, Vol. 70, No. 1, 1996.

11. K. V. Suresh Kumar, R. P. Kapoor, P. V. Ramalingam, B. Rajendran, G. Srinivasan, K. V. Kasiviswanathan, "Fast Breeder Test Reactor. 15 Years of Operating Experience," Paper presented at the Technical Meeting on Operational and Decommissioning Experience with Fast Reactors, IAEA-TM-25332, IAEA, 2002, pp. 15-27.

12. B. Battacherjee, "An Overview of RandD in Fuel Cycle Activities of AHWR," Paper presented at the 14th Indian Nuclear Society Conference, Kalpakkam, December 17-19, 2003, *www.indian-nuclear-society.org.in/conf/2003/1.pdf*.

13. George Perkovich, *India's Nuclear Bomb: The Impact on Global Proliferation*, Berkeley, CA: University of California Press, 1999, p. 428.

14. Nuclear Notebook, "India's Nuclear Forces, 2005," *Bulletin of the Atomic Scientists*, September/October 2005. Indian Defense ministry sources have mentioned plans for 300-400 weapons. Vivek Raghuvanshi, "India to Stay the Course on Nuke Doctrine," *Defense News*, November 1, 2004.

15. This assumes a burn-up of 1,000 megawatt-days per ton of heavy metal (MWd/tHM) and a plutonium content of 0.9 kg/t in the spent fuel.

16. We assume that both CIRUS and Dhruva (since 1988) have had an average annual availability factor of 70 percent, except for CIRUS between 1991-97, when we assume a 60 percent availability factor because of reported problems with aging. R. C. Sharma and S. K. Agarwal, "Research Reactor: Its Refurbishment and Future Utilisation," *BARC Newsletter*, June 2004. We assume Khushab has been operating since 1998 with a 70 percent availability factor.

17. We emphasize that all of this plutonium may not have been separated. ISIS estimates India may have accumulated 575 kg of weapons grade plutonium as of the end of 2004; see ISIS, *India's Military Plutonium Inventory, End 2004, www.isis-online.org/global_stocks/end2003/india_military_plutonium.pdf*.

18. Assuming a 7,000 MWd/tHM burn-up, thermal efficiency of 0.29, Monte Carlo N-Particle (MCNP) code calculations by Alexander Glaser and Jungmin Kang show the fresh spent fuel contains about 3.8 kg of plutonium per ton of heavy metal (tHM). As the spent fuel cools, its Pu-241 decays with a 14-year half-life and the overall plutonium content therefore decreases by about 1 percent over 5 years to 3.75 kg per ton of spent fuel. Indian PHWRs now have an average burn-up of 7,000 MWd/tHM. K. C. Sahoo and S. A. Bhardwaj, "Fuel Performance In Water Cooled Nuclear Reactors," Paper presented at the 14th Indian Nuclear Society Annual Conference, Kalpakkam, December 17-19, 2003, *www.indian-nuclear-society.org.in/conf/2003/12.pdf*.

19. Currently safeguarded reactors are Tarapur 1 and 2 and Rajasthan 1 and 2. The Tarapur reactors have a thermal efficiency of 31.2 percent, an average fuel burn-up of 19,500 MWd/tHM, and produce 8 kg/tHM of plutonium.

20. Z. Mian and A.H. Nayyar, "An Initial Analysis of 85-Krypton Production and Dispersion from Reprocessing in India and Pakistan," *Science and Global Security*, Vol. 10, No. 3, 2002.

21. *Ibid*.

22. Perkovich, pp. 428-430; Chengappa, pp. 417-418.

23. J. Carson Mark, "Explosive Properties of Reactor-Grade Plutonium," *Science and Global Security,* Vol. 4, No. 1, 1993, pp. 111-124.

24. Sanjeev Srivastava, "Indian P.M. Feels Political Heat," BBC, July 26, 2005, available from *news.bbc.co.uk/go/pr/fr/-/2/hi/south_asia/4715797.stm*.

25. A. Gopalakrishnan, "Indo-US Nuclear Cooperation: A Nonstarter?" *Economic and Political Weekly,* July 2, 2005.

26. Nuclear Power Corporation of India, *www.npcil.nic.in/PlantsInOperation.asp*.

27. Planning Commission, Government of India, *Mid-Term Appraisal of the Tenth Five Year Plan (2002-2007), planningcommission.nic.in/midterm/cont_eng1.htm*. Chapter 10, pp. 229-230.

28. *RWE Nukem*, December 2004, p. 24.

29. *Ibid*.

30. *Project Implementation Status Report of Central Sector Projects Costing Rs. 20 Crore and Above*, October-December 2005, Infrastructure and Project Monitoring Division, Government of

India, April 2006, *mospi.nic.in/pi_status_report_oct_dec2005.pdf*. The Turamdih plant is expected to be commissioned by December, 2006, "UCIL exploring uranium ore in Chattisgarh, Rajasthan, Karnataka," *PTI*, June 5, 2006.

31. "Interview with R. Kalidas," *RWE Nukem*, December 2004.

32. Xavier Dias, "DAE's Gambit," *Economic and Political Weekly*, August 6, 2005.

33. T. S. Subramanian, "Uranium Crisis," *Frontline*, January 13, 2006.

34. At Nalgonda, the Uranium Corporation of India claims it expects to mine 1,250 tons of uranium ore per day. "Environmental Clearance for Uranium Mining," *Hindustan Times*, December 12, 2005. Assuming an average grade of 0.04-0.05 percent, this implies 150-187.5 tons/year of uranium. For Kadapa, see MECON Limited (Ranchi), EIA/EMP Report For Tummalapalle Uranium Project, Uranium Corporation of India Ltd, 2006. As noted above, India expects a large increase in ore processing capacity in 2006 that can more than handle this increased demand.

35. T.S. Subramanian and Suhrid Sankar Chattopadhyay, "Back To Singhbhum," *Frontline*, January 13, 2006.

36. This includes under construction HWRs as they come into operation and excludes HWRs once they come under safeguards and can be fuelled by imported uranium. It also excludes CIRUS and Dhruva and uranium demand from the enrichment program, which add up to about 45 tons per year.

37. K Subrahmanyam, "India and the Nuclear Deal," *Times of India*, December 12, 2005.

38. "BARC Planning New Dhruva-Type Reactor," *Hindustan Times*, April 28, 1999.

39. Mark Hibbs, "Replication of Dhruva Reactor Proposed for Next Indian Economic Plan," *Nuclear Fuel*, May 8, 2006.

40. This possibility is suggested by Albright, Berkhout, and Walker, p. 267. In normal operation, a 200 MWe PHWR refueling machine would need to change 8 fuel bundles a day. A typical refueling machine apparently requires 2-3 hours to change 4-8 fuel bundles, see, e.g., *CANDU Fundamentals*, *canteach.candu.org/library/20040700.pdf*, p. 179. For 1,000 MWd/tHM burnup, such refueling would have to be repeated seven times a day.

41. A. H. Nayyar, A. H. Toor, and Z. Mian, "Fissile Material Production in South Asia," *Science and Global Security*, Vol. 6, No. 2, 1997, pp. 189-203.

42. A 220 MWe power reactor operating at 1,000 MWd/tHM burn-up would require a seven times higher refueling rate than at its normal, 7,000 MWd/tHM, operation. This appears to be possible given the on-line refueling capabilities of these reactors.

43. Uranium consumption is about 222 tons/year in production mode versus 32 tons in power mode.

44. Baltej Singh, P. D. Krishnani and R. Srivenkatesan, "Use of Depleted Uranium in Equilibrium Core of Standard PHWRs: A Complete Study," (Paper presented at the 16th Annual Conference of the Indian Nuclear Society, 2005), *www.indian-nuclear-society.org.in/conf/2005/pdf_3/topic_1/T1_CP5_Baltej_Singh.pdf*. The depleted uranium requirement is twice that of the natural uranium it replaces, in order to maintain reactor performance.

45. Singh, Krishnani, and Srivenkatesan, "Use of Depleted Uranium in Equilibrium Core of Standard PHWRs: A Complete Study."

46. Depleted uranium fuel is manufactured at the Nuclear Fuel Complex using uranium recovered by the reprocessing plant which handles spent fuel from CIRUS and Dhruva. C. Ganguly, "Manufacturing Experience Of PHWR and LWR Fuels," Paper presented at the 14th Indian Nuclear Society Conference, Kalpakkam, December 17-19, 2003, *www.indian-nuclear-society.org.in/conf/2003/8.pdf*. In a PHWR at a burnup of 1,000 MWd/tHM, the 0.7 percent U-235 in natural uranium fuel is reduced to 0.6 percent U-235, while fuel with a burnup of 7,000 MWd/tHM contains 0.2 percent uranium-235.

47. As of 2003, the Nuclear Fuel Complex at Hyderabad had produced about 76 tons of depleted uranium fuel. *Ibid*.

48. The four reactors at Kaiga also have been designated as military and may imply this site is to host another reprocessing plant and unsafeguarded breeder reactor, similar to the arrangement at Madras.

49. *Ibid*.

50. India plans a series of "FBR parks," each of which will have two to four FBRs, a dedicated reprocessing plant and a fuel fabrication plant, including at Kalpakkam; T. S. Subramanian, "A Milestone at Kalpakkam," *Frontline*, November 6, 2004.

51. *Design of Prototype Fast Breeder Reactor*, Indira Gandhi Centre for Atomic Research, December 2003, *www.igcar.ernet.in/broucher/design.pdf*. The plutonium content of the fuel is reported to be 20.7 percent in the inner core and 27.7 percent in the outer core, with approximately 91 percent of the total power generated in the core; D. G. Roychowdhury, *et al.*, "Thermal Hydraulic Design of PFBR Core," *LMFR Core Thermohydraulics: Status and Prospects,* IAEA-TECDOC-1157, June 2000, *www.iaea.org/inis/aws/fnss/fulltext/1157_3.pdf*.

52. We assume a core breeding ratio of 0.68 and an overall breeding ratio of 1.05. Note that Japan's Monju and the cancelled U.S. Clinch River fast breeder reactors had core breeding ratios of 0.6-0.75; S. Usami, *et al.*, *Reaction Rate Distribution Measurement and the Core Performance Evaluation in the Prototype FBR Monju*, last updated July 5, 2005, *aec.jst.go.jp/jicst/NC/tyoki/sakutei2004/sakutei17/siryo41.pdf*. For this range of core breeding ratios, the PFBR would produce about 164-109 kg of weapons grade plutonium. Preliminary results from MCNP calculations on PFBR plutonium production support this range of plutonium production. Alexander Glaser, private communication.

53. T. S. Subramanian, "A Milestone at Kalpakkam," *Frontline*, November 6-19, 2004, *www.hinduonnet.com/fline/fl2123/stories/20041119003210200.htm*.

54. The spent fuel from the breeder would need to cool before it could be reprocessed and the plutonium recycled, and so an initial plutonium stock for two cores, about four tons in total, is required for each breeder.

55. Zia Mian and M. V. Ramana, "Beyond Lahore: From Transparency to Arms Control," *Economic and Political Weekly*, April 17-24, 1999; Zia Mian, A. H. Nayyar and M. V. Ramana, "Making Weapons, Talking Peace: Resolving The Dilemma of Nuclear Negotiations," *Economic and Political Weekly*, July 17, 2004; R. Rajaraman, "India-U.S. Deal and the Nuclear Ceiling," *The Hindu*, September 10, 2005; R. Rajaraman, "Nurturing the Indo-US Agreement" in *The Debate on the Indo–US Nuclear Cooperation*, Delhi Policy Group and Bibliophile South Asia, 2006.

56. Matthew McKinzie, *et al.*, "The Risks and Consequences of Nuclear War in South Asia," in *Out of the Nuclear Shadow*, Smitu Kothari and Zia Mian, eds., Delhi: Lokayan and Rainbow Publishers and London: Zed Books, 2001.

57. R. Rajaraman, "Save the Indo-US Agreement," *Hindustan Times*, November 5, 2005.

58. R. Rajaraman, "Cap the Nuclear Arsenal Now," *The Hindu*, January 25, 2005, R. Rajaraman, "Towards De-Nuclearisation of South Asia," paper presented at the 2nd Pugwash Workshop on South Asian Security, Geneva, Switzerland, May 16-18, 2003.