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Fissile Material Production Potential in South Asia

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The cases of India and Pakistan show how civilian nuclear activities could potentially contribute significantly to the production of weapons-grade fissile materials. The paper estimates the amount of weapons-grade plutonium that could have been produced from unsafeguarded power reactors in India if these reactors were operated deliberately for this purpose, and the rate at which Pakistan could accumulate weapons-grade uranium if it used its stockpile of low-enriched uranium as feed material to its enrichment facilities. These estimates are not judgments of what these countries have actually done or intend to do, but are forwarded to call attention to an issue that will have to be addressed under a fissile material production cutoff in South Asia and elsewhere.

INTRODUCTION

The prospect of a Fissile Material Cut-off convention raises important questions about the accumulated fissile material stocks in countries which are known to have nuclear weapons capability. We look here at the cases of India and Pakistan. These two countries have followed different routes to produce fissile material: India has reprocessed spent fuel from nuclear reactors to extract plutonium, while Pakistan has relied on uranium enrichment.

While there are estimates available of weapons-grade plutonium (WGPu) production in India, they have assumed that the Indian nuclear power program has made no contribution to such production. Similarly, estimates for uranium enrichment in Pakistan have focused on production of highly enriched uranium (HEU) and not examined the stockpiling of low enriched uranium (LEU) and the time it would take to turn such stockpiled material into weapons-grade material.

The data on which to base calculations that could address these concerns are limited. However, there are data on the total power production by the nuclear reactors, fuel fabrication and reprocessing capacity in India that can

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be used to make some kind of worst-case estimate. For Pakistan, the data are even more scarce, and estimates have to be made on the basis of earlier assumptions in the literature about Pakistan's enrichment capacity.

With these constraints in mind, we have estimated the amount of weapons-grade plutonium that could have been produced from unsafeguarded power reactors in India if these reactors were operated deliberately for this purpose. We have also evaluated the time needed for Pakistan to double its estimated HEU stockpile if it decides to resume HEU production and uses a possible LEU stockpile as feed material for the enrichment process.

PLUTONIUM ACCOUNTING IN THE INDIAN NUCLEAR FUEL CYCLE

Given that India has a large and diverse civilian nuclear program, and that most of it is unsafeguarded (see figure 1), it would be of interest to attempt an audit of the Indian nuclear fuel cycle. Given also that India has extracted WGPu from its reactors, a point of major interest would be to estimate the size of its plutonium holdings over the years.

Although plutonium with any composition of isotopes is weapons-usable, larger concentrations of isotopes other than Pu-239 pose serious problems when used in weapons. Pu-240 has a large spontaneous fission rate, which will lead to reduced explosive yields in relatively unsophisticated weapons designs. Pu-241 decays to Am-241 which is a strong source of X-rays and gamma-rays, making the material difficult to handle.[1] On the other hand, weapons cores made with weapons-grade plutonium (containing more than 94 percent Pu-239) can be safely stocked for a long time. That is why, given an opportunity, a country with a Pu-based nuclear weapons program would prefer WGPu.

Albright, Berkhout and Walker[2] have estimated that by 1995 the total stock of WGPu acquired by India is about 425 kg. This would consist of plutonium extracted from the fuel discharges of India's two large research reactors, Cirus and Dhruva, and from the first discharges of five unsafeguarded power reactors, Madras I and II, Narora I and II, and Kakrapar I. The first discharges were at low burn-up, and, therefore, the separated plutonium would have a very high concentration of Pu-239.

The Indian commercial nuclear program today consists of two boiling water reactors (BWRs), Tarapur I and II, and eight CANDU-type pressurized heavy water reactors (PHWRs). Of the latter, six (including one new reactor, Kakrapar II, which became critical in early 1995 and is expected to go commercial in 1996) have been locally manufactured and are unsafeguarded. Six more PHWRs, also locally manufactured and unsafeguarded, are under various stages of construction.

The CANDU reactors allow on-line change of fuel without any compromise on their power output. This makes it possible to use a part of their fuel at low burn-up to produce WGPu. Because of this, "India could, in principle, dedicate one or more of its power reactors to weapons-grade plutonium production, although with a sizable penalty in fuel costs."[3]

Is the penalty in fuel costs really prohibitive? How much additional fuel-can India afford if it were to follow this course? Would there be limitations on reprocessing the additional low burn-up fuel discharges?

Answers to these questions can be provided by an audit of the Indian nuclear fuel cycle, concentrating only on that part of it which covers processes from fuel fabrication to reprocessing, shown in figure 1.

The Revised Accounting

Fuel Fabrication

The total listed fuel fabrication capacity of India is 405 tons of heavy metal per year (tHM/y), of which twenty-five tons are fabricated as slightly enriched fuel for the two boiling water reactors at Tarapur.[4] Of the 385 tons of natural uranium fuel that can be produced at the Trombay and Hyderabad facilities, about 35 tons a year are consumed in the two research reactors Cirus and Dhruva,[5] and the remaining 350 tons a year are, in principle, available for use in the heavy water power reactors. This has been the situation since 1984, the year when the first of the unsafeguarded Indian power reactors became operational, and the date from which we commence our fuel accounting.

Fuel Consumption

The 350 tons of natural uranium fuel per year is presently available for consumption in eight heavy water power reactors. Two of these, Rajasthan I and II, which are under international safeguards, need an annual fuel reloading of 30 tons each when running at full capacity, while the remaining six reactors, which have identical design specifications, need 33 tons of annual fuel reloading for a 100 percent capacity operation. The latter six have had a first fuel load of 56 tons each. These numbers define the maximum fuel demand of the eight reactors.[6]

But the actual fuel consumption of a reactor depends upon the fraction of time it has been run and the capacity at which it was operated. The capacity factor of a reactor can be estimated from the published figures of its gross annual energy production. The actual yearly fuel consumption of a reactor can

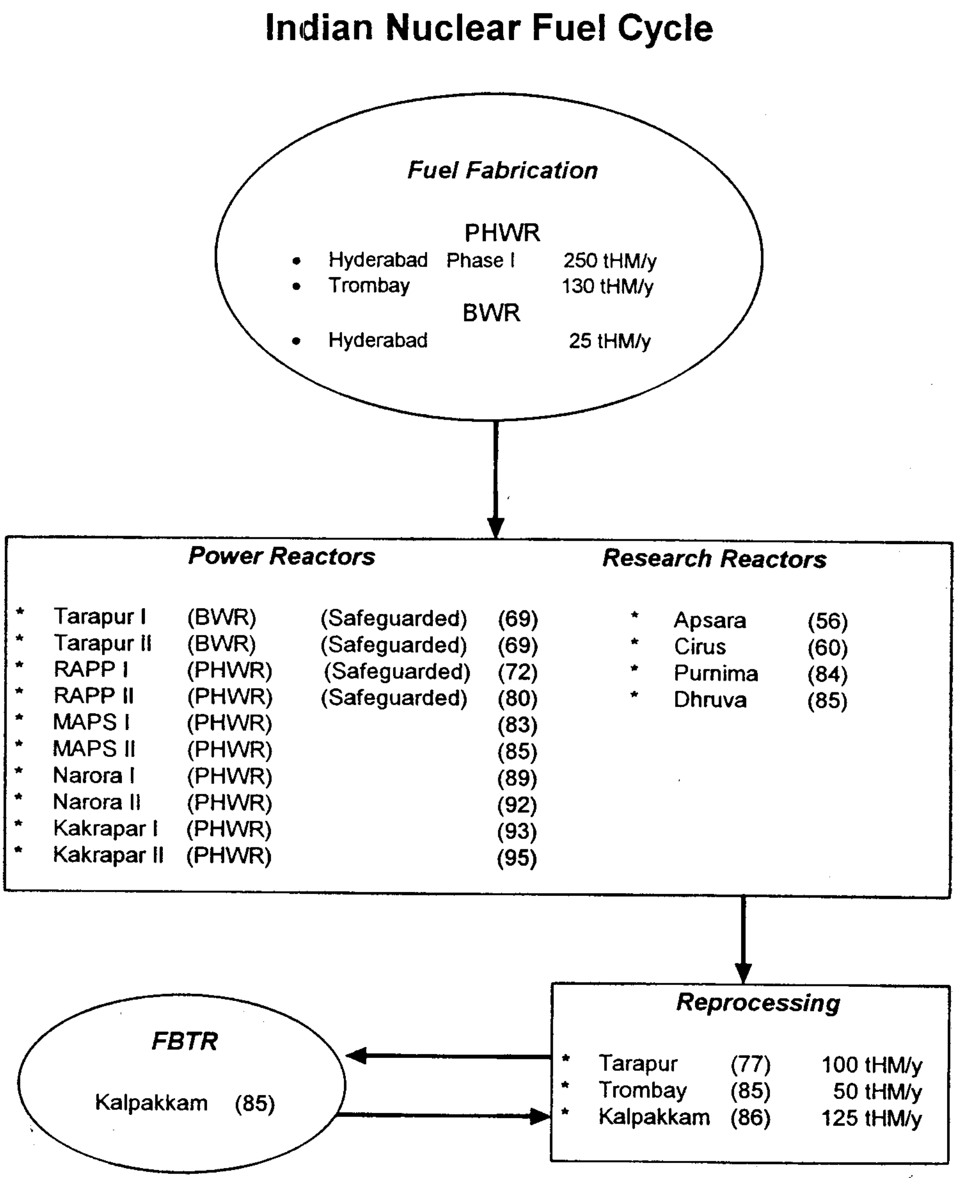

Figure 1: Indian nuclear fuel cycle.

Table 1: Fuel consumed by the safeguarded power reactors.

	Rajasthan I		Rajasthan II		
Year	Capacity Factor %	Fuel Consumed (tHM)	Capacity Factor %	Fuel Consumed (tHM)	Total Fuel Consumed (tHM)
1984	0	0	51.53	15.5	15.5
1985	13.49	4.05	57.75	17.33	21.4
1986	0	0	70.05	21.01	21.0
1987	14.65	4.40	66.88	20.07	24.5
1988	24.23	7.27	72.21	21.66	28.9
1989	19.92	5.98	63.58	19.07	25.0
1990	23.29	6.99	63.15	18.95	25.9
1991	12.53	3.76	51.62	15.49	19.3
1992	4.27	1.28	50.45	15.14	16.4
1993	11.22	3.37	66.48	19.9	23.3
1994	0.44	0.13	32.9	9.87	10.0
1995*	20.0	6.0	70.0	21.0	27.0
Total		**43.23**		**214.99**	**258.2**

Guessed at the rates of 1994.

then be calculated from the capacity factor and its designed burn-up rate in MWd/t. Table 1 shows the actual amount of fuel consumed from 1984 to 1995 by the two safeguarded Rajasthan reactors, each of which has a design burn-up rate of 6,700 MWd/t.[7] The actual power production from these safeguarded reactors suggests that as against a nominal fuel requirement of 720 tons over the twelve year period from 1984 to 1995 (2 x 30 tons/y x 12 years), the reactors have consumed only about 260 tons.

A similar exercise can be undertaken for the remaining six power reactors, each of designed power output of 220 MWe. Published figures of total electricity produced by these reactors allows calculation of their capacity factors. These are shown in table 2. The capacity factors can then be used to calculate fuel requirements under different assumptions of fuel burn-up. If the reactors

Table 2: Fuel requirement of the unsafeguarded PHWRs if they were operated at the low burn-up rate of 1,000 MWd/t. *CF = capacity factor; Fuel = fuel (in tons) that would have been needed to run the reactor at the low burn-up rate of 1,000 MWd/t; (1) = the first core inventory.*

Year	*Madras I*		*Madras II*		*Narora I*		*Narora II*		*Kakrapar I*		*Kakrapar II*		Total Fuel Requirement
	CF %	Fuel tHM	CF %	Fuel tHM	CF %	Fuel tHM	CF %	Fuel tHM	CF %	Fuel tHM	CF %	Fuel tHM	tHM
1984	65.1	144	-	56(1)	-	-	-	-	-	-	-	-	200
1985	45.9	101.5	3810610 6.6	85.3	-	-	-	-	-	-	-	-	186.8
1986	41.5	91.8	44	97.3	-	-	-	-	-	-	-	-	189.1
1987	58.3	128.9	62	137.5	-	-	-	-	-	-	-	-	266.4
1988	68.1	150.6	34.8	76.9	-	-	-	-	-	-	-	-	227.5
1989	23.9	52.8	25.2	55.7	-	-	-	-	-	-	-	-	108.5
1990	50.1	110.8	56.4	124.7	-	56(1)	-	-	-	-	-	-	291.5
1991	28.6	63.2	60.5	135.8	28.2	62.3	-	56(1)	-	-	-	-	317.3
1992	59.7	132	36.9	81.6	42.8	94.6	33.5	74.1	-	56(1)	-	-	438.3
1993	29.8	65.9	52.9	117	18.6	41.1	5.16	11.4	45.1	99.7	-	-	335.1
1994	44.8	99.2	54.6	120.7	0	0	42.9	94.9	5.1	11.3	-	-	326.1
1995*		100		120		41		10		98		56(1)	425

* Guessed at the rates of 1994.

were operated at the design burn-up of 6,700 MWd/t, altogether they would have consumed approximately 730 tons of fuel over the twelve years. If so, the total consumption of fuel for the eight commercial reactors would be about 990 tons, far smaller than the reported 4,200 tons of fuel fabrication capacity available during this period (350 t/y x 12 years).

If, however, instead of operating at the design burn-up rate of 6,700 MWd/t, these unsafeguarded reactors were operated at the weapons-grade plutonium producing low burn-up rate of 1,000 MWd/t, their fuel require ments would be increased by a factor of 6,700/1000. The annual fuel requirement of the six unsafeguarded power reactors if they were used to produce weapons-grade plutonium is shown in table 2. The total fuel requirement then is about 3,300 tons, still less than the capacity available. Thus, probably, India has almost always had enough fuel to operate its unsafeguarded power reactors in a WGPu production mode: in this regard, there never was a prohibitive "penalty in fuel costs."[8] If there was a shortage of fuel, as in the later years of 1992, 1993 and 1995, it could easily be covered by the unused fuel stocks from the previous years. However, we do not know if India has had the handling capacity at the reactors to change the fuel with a frequency 6.7 times that at the design burn-up or what the cost-penalty of doing that might be.

Reprocessing

India has three reprocessing facilities—at Trombay, Tarapur and Kalpakkam— with a total listed capacity of 275 tHM/y.[9] The Trombay facility, with a capacity of 50 tHM/y is believed to be dedicated to the metallic fuel discharges of the Cirus and Dhruva research reactors. There is uncertainty about the remaining reprocessing capacity of India. Although the Kalpakkam facility is listed as operational since 1986 in the World Nuclear Industry Handbooks, and quoted at several places,[10] it is generally held that only the Tarapur facility is available for reprocessing spent fuel from the power reactors. In order to keep our estimates on the conservative side, we shall also take this to be true. The Tarapur facility is not safeguarded when reprocessing fuel from unsafeguarded reactors. It had a nominal capacity to reprocess 100 tHM/y until 1990, and has been upgraded to 150 tHM/y since 1991.

As shown in table 3, the reprocessing capacity is what would have limited production of WGPu if India had decided from the beginning to run its power reactors in the WGPu production mode. If it did so, in addition to the 425 kg of WGPu obtained from research reactors as estimated by Albright *et al.*,[11] India could have produced an additional 1,450 kg of WGPu. The uncertainty in the reprocessing capacity introduces large uncertainties in the final estimates of maximum potential WGPu production. Whenever it is ready, the Kalpakkam

Table 3: Amount of weapons-grade plutonium that could be obtained from unsafeguarded power reactors. *(1) = at the burn-up rate of 1,000 MWd/t; (2) = at the rate of 1 kilogram of WGPu from one ton of low burn-up discharges.*

Year	Fuel Discharges from power reactors (tHM) (1)	Reprocessing Capacity (tHM)	Amount of Extracted WGPu (kg) (2)
1984	144	100	100
1985	187	100	100
1986	189	100	100
1987	266	100	100
1988	227	100	100
1989	108	100	100
1990	235	100	100
1991	261	150	150
1992	382	150	150
1993	335	150	150
1994	326	150	150
1995	369	150	150
Total	**3,029**	**1,450**	**1,450**

II reprocessing plant, listed as under construction with a nominal capacity of 1000 tHM/y,[12] could, in principal, extract about 1,500 kg WGPu from the accumulated 1,579 tons of as yet un-reprocessed spent fuel in less than two years.

Plutonium from the Fast Breeder Reactor

The Indian fast breeder test reactor (FBTR) uses as fuel in its core a mixture of plutonium and uranium, plutonium being about 70 percent of the total core mass.[13] An FBR is designed to breed plutonium in the jacket of depleted or natural uranium surrounding the core. The most noticeable aspect of an FBR is that while reactor grade plutonium is used in the core, super-grade plutonium (containing more than 93 percent Pu-239) can be produced in the jacket. In fact, a FBR is a very good device for producing super-grade plutonium.

Not much information on the burn-up of the Indian FBTR is available in the open literature. Albright *et al.*[14] indicated that 0.365 kg of super-grade plutonium is produced in a U-238 jacket per MWe-year of energy production from the French fast reactor Phenix. We assume that the same may also be true for the Indian FBR. The 11 MWe Indian FBTR went critical in 1985, but evidently did not reach full-power operation until 1990. If we assume that it ran after 1990 at 60 percent of its capacity, it could have produced roughly 12kg of super-grade plutonium during the ensuing five years

Need for Large Stocks

The question then is: Is it plausible that India has actually produced WGPu from its power and test-breeder reactors? To have done so, it would have had to have capability, opportunity and motivation. That it has had the capability and opportunity has been suggested by the above analysis. It seems within the realm of possibilities that India could have used its power reactors to produce 1,450 kg of WGPu beyond the estimated 425 kg from research reactors, although we wish to stress that there is no evidence it has actually done so.

What about motivation? Certainly, India claims to have reasons to maintain a nuclear option. One is the immediate concern from China and Pakistan both of whom have long-standing disputes with India, and whom India and the world at large suspect of collaborating with each other in nuclear matters. India's nuclear option is said to guard against this threat. As long as this threat perception exists, India is likely to make its nuclear capability more and more credible.

Secondly, India has persistently refused to abandon its nuclear option as long as the possession and use of nuclear weapons are regarded as legitimate for the five nuclear weapon states. India's opposition to regional nuclear disarmament in South Asia, in part, reflects this policy. Since it has always been apparent that the nuclear weapon states wish to retain their nuclear status for an indefinite period, India claims to have a reason to increase its stockpile of nuclear material.

However, even granted India's wish for some nuclear weapons capacity, shouldn't the fissile material for about a hundred or so weapons be sufficient for its perceived security needs? One possible reason could be a desire to have weapons of higher yield. A core can be made with as little as 3-6 kg of plutonium. Thus, the 425 kg of WGPu estimated to have been produced from Cirus and Dhruva would be sufficient to make on the order of 100 weapons. However, it is known that the yield of nuclear weapons increases non-linearly with the number of critical masses in the core. The yield is 60 times higher with only 2.5 critical masses. If India does want to go for high yield nuclear weapons, it will have to have cores of higher critical masses, and hence will need larger stockpiles. The additional WGPu is potentially available from the reprocessing if spent fuel from the unsafeguarded power reactors could thus be used to increase the yield of India's nuclear weapons.

The increasing evidence of an advanced Indian hydrogen bomb program suggests another use for the extra WGPu.[15] In the Teller-Ulam H-bomb design, which is said to be fool-proof, along with the primary or atomic bomb trigger, a cylinder of perhaps several critical masses worth of Pu is used as a "spark-plug" initiator for the fusion.[16]

PAKISTAN'S URANIUM STOCKPILE

Over the last two decades, Pakistan has managed to put in place a uranium enrichment capability that is widely believed to have delivered weapons-grade uranium (containing at least 90 percent U-235). One clear confirmation of this was the statement by the Pakistani Foreign Secretary to The Washington Post[17] that Pakistan had "permanently frozen production of highly enriched uranium and weapons cores." In other words, Pakistan had been producing weapons-grade uranium and fashioning cores from it, but was doing so no longer.

This interpretation matches a close reading of assessments by US officials that Pakistan is able to assemble nuclear weapons within a very short time. [18] The use of "assemble" rather than "produce" suggests that all the parts are already available which presumably includes the weapons cores.

The recent checkered history of Pakistan's uranium enrichment is quite confused.[19] It is believed that uranium enrichment to weapons-grade first stopped in 1989, was restarted, and then stopped again. There is some ambiguity about the latter date, however; a former Foreign Secretary has claimed that this "cap" was put in place in 1991, while a former Chief of Army Staff claims it happened in 1990. What does seem clear though is that rather than closing down the facilities for uranium enrichment, a much lower (than weapons-grade) level of enrichment was selected and activity continued. It has been suggested by the former Pakistani Chief of Army Staff that an enrichment limit of 3–5 percent was set. This history of uranium enrichment activity would have led to two stockpiles of enriched uranium. The first is a stockpile of weapons-grade uranium (90 percent U-235) some of which may have been turned into weapons cores. Evidently, this stockpile is no longer being augmented. The second is the stockpile of low-enriched uranium (taken to be 3 percent–5 percent U-235) or LEU which began to be accumulated in 1990–1991, and is still accumulating.

Using the standard equations for uranium enrichment (equation 1),[20] we have calculated the size of the low enriched uranium stockpile. The assumptions are that low level enrichment took place for 5 years (say July 1991 to July 1996), that the whole of the enrichment capacity once used to produce weapons-grade material was being used to produce low enriched uranium during this period, and that the tails assay used was 0.003.

The total Pakistani enrichment capacity is estimated at between 9,000 SWUs (kilogram Separative Work Units per year, which has dimensions of kg/year) and 15,000 SWUs.[21] These estimates are for the Kahuta enrichment facility. There are reported to be other enrichment facilities in Pakistan; an experimental one at Sihala, and another at Golra, for which no capacity figures are available.[22]

In terms of the concentrations N_F, N_P and N_W of U-235 in the feed, product and waste material respectively, and the product P in kg of enriched uranium, the separative capacity SWU (in kg/year) is given by the relation:

$$SWU = P \cdot \left(V(N_P) + \frac{N_P - N_F}{N_F - N_W} V(N_W) - \frac{N_P - N_W}{N_F - N_W} V(N_F) \right) \qquad (1)$$

where the value function *V(N)* is given by:

$$V(N) = (2N - 1)\, ln \left(\frac{N}{1 - N} \right) \qquad (2)$$

From equation 1, the total production alternatively of 3 percent, 5 percent and 20 percent enriched uranium over a period of five years, from July 1991 to July 1996 can be calculated. Table 4 shows the results for the two assumed values of the separation capacity. If Pakistan has been producing nothing but LEU from its centrifuge enrichment facility at Kahuta for the last five years at full capacity, it could have produced between 6–22 tons of 5–3 percent enrichment uranium (or lesser quantities of 20 percent uranium).

The Senate Foreign Affairs Committee[24] recommended that the government change its policy of limiting enrichment to 3–5 percent U-235 and resume production of weapons-grade material before a fissile material cut-off convention enters into force. The justification given is that a larger stockpile of weapons-grade material may be necessary to ensure sufficiency.

One way to do this quickly is for the LEU to be used as feed to a cascade to enrich the uranium to 90 percent uranium. An interesting figure of merit describing the potential of such a cascade is the shortest time to produce a specified quantity of weapons-grade uranium from the feedstock of LEU available. This time is found by choosing a tails assay, N_W, such that:

$$N_W = \frac{FN_F - PN_P}{F - P} \qquad (3)$$

where F and P are respectively the quantities of feed available and specified product; N_F and N_P are the enrichment levels of the feed and product.[23]

The time is then given by the following:

$$t = \frac{P}{SWU} \cdot \left(V(N_P) + \frac{N_P - N_F}{N_F - N_W} V(N_W) - \frac{N_P - N_W}{N_F - N_W} V(N_F) \right)^{-1} \qquad (4)$$

To illustrate such calculations, we specify a product of 200 kg 90 percent uranium—roughly double the quantity of weapons-grade uranium estimated by Albright, *et al.* (130–220 kg). Table 5 shows the results of the calculations based on this assumption and the estimates shown in table 4 for feedstocks of LEU possibly now available to Pakistan.

For example, in table 4, we see that Pakistan could have 13,123 kg of 3 percent LEU available (based on a 9,000 SWU/y capacity). Then N_W may be calculated by:

$$N_W = \frac{(13,123)(0.03) - (200)(0.90)}{13,123 - 200} = 0.0165$$

Putting N_W into equation 4, gives, for the bracketed quantity, 42.5 SWUs. That is, it will take 42.5 SWUs to produce 1 kilogram of 90 percent uranium from a feedstock of 3 percent uranium, and a tails assay of 1.65 percent. To produce 200 kg of 90 percent uranium would then require 8,500 SWUs or approximately 49 weeks for a cascade rated at 9,000 SWUs per year.

The results given here suggest that while Pakistan could resume HEU production, either as a response to an imminent agreement on a fissile material cut-off treaty, or in response to a major political crisis with India, it would take between a few months and about a year to substantially contribute to its existing HEU stocks. The relatively short times involved suggest that rather than immediately moving to produce weapons-grade material, Pakistan might instead simply continue to produce LEU. The larger stockpile of LEU would give it a larger potential to produce weapons-grade uranium, without significantly adding to the time penalty involved in transforming LEU into weapons-grade uranium.

Table 4: Lower and upper estimates for the LEU stockpile accumulated over five years, assuming natural uranium feed (input) and 0.3 percent U-235 in the tails (waste). This calculation also assumes that the supply of natural uranium is not a constraint. The figures for 20 percent enrichment are given just for completeness, because 20 percent enrichment is usually taken to be the upper limit at which material is still classified as LEU.

Level of Enrichment (%)	Mass of Product (kg) for 9,000 SWUs	Mass of Product (kg) for 1,500 SWUs
3	13,123	21,871
5	6,245	10,407
20	1,173	1,956

Table 5: Time in weeks to produce 200 kg of weapons-grade uranium from the LEU stockpile.

Enrichment Level of Feed Material (% U-235)	Time in Weeks for 9,000 SWUs	Time in Weeks for 15,000 SWUs
3	49	26
5	33	17
20	10.5	5

CONCLUSION

Most of the discussion surrounding a fissile material cut-off convention has focused on the production of weapons-grade material. However, the case of India and Pakistan shows how ostensibly civilian nuclear activities (operations of commercial power reactors in India and the production of LEU in Pakistan) provide enormous potential for the production of much larger than expected amounts of weapons-grade fissile materials.

Thus, any future effort at bringing India and Pakistan into the folds of a fissile material production cut-off (FMCO) regime, regional or international, must ensure that there is adequate safeguarding of civilian nuclear programs.

The demand that international arms control treaties be universal and non-discriminatory, which has proved troublesome for the CTBT, suggests that any FMCO process will require bringing all civilian nuclear programs into the arms control process.

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1. See, for example, F. von Hippel, "Physics Today," June 1995, p. 26.

2. Albright, D., F. Berkhout and W. Walker, *World Inventory of Plutonium and Highly Enriched Uranium, SIPRI*, (Oxford University Press, 1993), p. 161.

3. Albright *et al.*, p. 159.

4. *World Nuclear Industry Handbook*, (1993 and 1994).

5. This figure has been estimated from the total WGPu production from the two research reactors, as estimated by Albright *et al.* (see endnote 2). A rule of thumb is that each ton of fuel burnt at 1,000 MWd/t produces 1 kilogram of WGPu.

6. *World Nuclear Industry Handbook*, op. cit., (1993 and 1994).

7. The total yearly electrical energy production from each reactor is reported in the *Nucleonics Week*.

8. Albright *et al.*, op. cit., p. 159.

9. *World Nuclear Industry Handbook*, op. cit., (1993 and 1994).

10. See, for example, *A Guide to Nuclear Activities in India and Pakistan*, "US Arms Control and Disarmament Agency Report," (March 1994), and the references cited therein.

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14. Albright *et al.*, p. 44.

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21. Albright *et al.*, op. cit., p. 161.

22. Spector, L., *Nuclear Ambitions—The Spread of Nuclear Weapons 1989–1990*, (Westview Press, 1990).

23. For a specified product, *P*, there would not be enough feed available to allow a higher tails assay. A cascade using a lower tails assay and the same feedstock could produce a quantity of product greater than *P*, but would take longer to do so.

24. "The Daily Dawn," Karachi, (July 21, 1995).