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The Myth of "Denatured" Plutonium
Reactor-Grade Plutonium and Nuclear Weapons

Part Six: Reactor-Grade Plutonium in the Nuclear Weapon Programs of Sweden, Pakistan and India

This paper is the sixth in a series to comprehensively examine the nuclear weapon dangers posed by reactor-grade plutonium. The first paper described some of the basic properties of plutonium, how it is classified into different grades, the variation in reactor fuel burnup and how plutonium's properties can vary depending on the initial fuel enrichment and burnup of the reactor fuel that produces the plutonium.[2] The second paper provided a short history of views regarding the nuclear weapon dangers of reactor-grade plutonium and discussed how the nuclear industry's desire to recycle plutonium has led it to downplay its dangers.[3] The third paper showed that the problem of the predetonation of an unboosted implosion fission weapon is not an impediment to the use of reactor-grade plutonium to produce nuclear weapons.[4] The fourth paper demonstrated that the increased heat content of reactor-grade plutonium produced in Light Water Reactors (LWRs) does not prevent such material from being used to produce nuclear weapons.[5] The fifth paper demonstrated that the increased radiation and critical mass of reactor-grade plutonium also does not prevent it from being used to produce nuclear weapons.[6]

As was discussed in Part One of this series, the preferred isotopic composition of plutonium for nuclear weapons would be pure Pu 239 but it is not feasible to produce large quantities of such plutonium. Instead countries have been forced to use weapon-grade plutonium that contains at least several percent Pu 240. But what if only reactor-grade plutonium were available? If reactor-grade plutonium were truly unsuitable for use in nuclear weapons, then countries that had access only to reactor-grade plutonium would have to give up their attempt to produce nuclear weapons. But both Sweden and Pakistan were not deterred and were prepared to move ahead using reactor-grade plutonium. That these two countries did not produce nuclear weapons from reactor-grade plutonium had nothing to do with the properties of this material. In the case of

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[2] Gregory S. Jones, "The Myth of "Denatured" Plutonium, Reactor-Grade Plutonium and Nuclear Weapons, Part One: Introduction, Plutonium Basics, Definitions of Grades of Plutonium, Variation in Fuel Burnup, and the Properties of Plutonium Produced in Different Reactor Fuels," July 26, 2016. Link

[3] Gregory S. Jones, "The Myth of "Denatured" Plutonium, Reactor-Grade Plutonium and Nuclear Weapons, Part Two: Short History of Reactor-Grade Plutonium and Plutonium Recycle: Why Does the Nuclear Industry Downplay the Danger of Reactor-Grade Plutonium, September 1, 2016. Link

[4] Gregory S. Jones, "The Myth of "Denatured" Plutonium, Reactor-Grade Plutonium and Nuclear Weapons, Part Three: Predetonation," October 25, 2016. Link

[5] Gregory S. Jones, "The Myth of "Denatured" Plutonium, Reactor-Grade Plutonium and Nuclear Weapons, Part Four: Heat," December 15, 2016. Link

[6] Gregory S, Jones, "The Myth of "Denatured" Plutonium, Reactor-Grade Plutonium and Nuclear Weapons, Part Five: Radiation and Critical Mass," February 27, 2017. Link

Sweden, it wound down its nuclear weapon program before it made any decision to produce nuclear weapons. In the case of Pakistan, U.S. counteraction blocked the French sale of the reprocessing plant that was needed to obtain the plutonium and the theft of centrifuge technology from the Netherlands provided Pakistan with other options.

India has access to weapon-grade plutonium but the quantities it has produced may be insufficient for the needs of its nuclear arsenal. India has retained the option to use reactor-grade plutonium in its nuclear weapon program by exempting eight of its nuclear power reactors from International Atomic Energy Agency (IAEA) safeguards. India may have already exercised this option such that up to half of its nuclear arsenal could be composed of nuclear weapons made with reactor-grade plutonium.

This paper will not provide comprehensive histories of these countries' nuclear weapons programs but will simply discuss the role reactor-grade plutonium played in them. As far as I am aware this paper will be the first to discuss the role of reactor-grade plutonium in the nuclear weapon programs of Sweden and Pakistan, even though this information has been available for decades.

Sweden's Nuclear Weapon Program

In 1945, Sweden found that it needed to explore and develop a number of new technologies that had been used in World War II if it was to maintain the strong defense vital to ensure its neutrality. Jet aircraft and radar were two such technologies, nuclear weapons were another. Sweden was also interested in the possibilities of nuclear power and its nuclear development program focused on both nuclear power and nuclear weapons, though its public statements emphasized the former rather than the latter. Over time, Sweden's military generated a requirement for one hundred simple fission weapons with yields in the low tens of kilotons. Sweden intended to employ the weapons tactically to disrupt a Soviet invasion by striking embarkation ports, invasion forces at sea or even enemy forces that had landed on Swedish territory.[7]

Sweden planned to produce plutonium using natural uranium fueled heavy water reactors. Sweden possesses large uranium deposits which had been discovered at the beginning of the twentieth century when there was an interest in mining radium.[8] In the 1950s, Sweden began to develop its resources to produce uranium that was unencumbered by foreign restrictions. However, the concentration of uranium in the Swedish ore is only 200 ppm.[9] With the discovery of uranium deposits in the U.S. with ten times this concentration of uranium, the Swedish deposits were uneconomical.[10] Only 215 metric tons of uranium were produced before production was shut down in 1969.

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[7] Paul M. Cole, "Sweden without the Bomb: The Conduct of a Nuclear Capable Nation without Nuclear Weapons," RAND, Santa Monica, CA, 1994.

[8] Jan Lindholm, "The Ranstad Uranium Mine in Sweden," April 27, 2007.

[9] V. E. McKelvey, "Uranium in the Upper Cambrian Black Shale of Sweden," United States Department of the Interior, Geological Survey, January 1955.

[10] Even richer deposits were later discovered in Canada and Australia. Although the Swedish deposits may contain up to one million metric tons of uranium, they are no longer counted as conventional uranium resources. "Uranium

Sweden hoped to acquire large quantities of heavy water without use restrictions from Norway but ultimately received most of its heavy water from the U.S. Sweden realized that the only likely way to acquire large quantities of heavy water without use restrictions would be to produce it itself. Sweden has large hydroelectric resources and could use electrolysis to produce heavy water in a manner similar to Norway. Sweden performed pilot studies but ultimately did not build its own heavy water plant.[11]

Sweden would also need to reprocess the spent uranium fuel in order to separate the plutonium. Sweden constructed a plutonium laboratory which contained a number of glove boxes and performed experiments on small quantities of plutonium acquired from foreign countries. The plutonium laboratory was completed in 1959. This facility had a limited plutonium reprocessing capability. Sweden considered building a large-scale reprocessing plant but ultimately did not.[12]

Sweden's first nuclear reactor, the R1, started operation in 1954. It used French uranium and Norwegian heavy water and was free of any encumbrances on the use of the plutonium produced by the reactor. However, with a power level of 600 kW it could only produce about 100 grams of plutonium per year.

Sweden began to construct its first nuclear power reactor, Agesta, in 1957. Agesta went into commercial operation in 1964.[13] The reactor was an indigenous design which used natural uranium fuel and heavy water as the moderator. It had a thermal power output of 65 MW which was later increased to 80 MW. It used 76 metric tons of heavy water, a significant portion of which came from the U.S. Agesta could produce about 15 to 20 kilograms of plutonium per year, which would be enough for about three nuclear weapons per year. Agesta's rate of plutonium production was too low to produce a one hundred weapon arsenal in a reasonable amount of time and for this reason the focus on plutonium production for nuclear weapons was on the larger follow-on power reactor, Marviken.

In 1960, Sweden designed the Marviken power reactor as a scaled-up version of Agesta.[14] With a 400 MW thermal power output it would produce about 110 kilograms of plutonium per year which would be enough for about eighteen weapons per year. Such a reactor would be able to produce enough plutonium for a one hundred weapon arsenal in about five and one half years.

However, the desire to produce a more economical nuclear power reactor led to a major redesign of the Marviken reactor in 1962 and 1963. The reactor had a number of unusual features

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2014: Resources, Production and Demand," Nuclear Energy Agency and Organization for Economic Co-operation and Development, 2014.

[11] Thomas Jonter, "Nuclear Weapons Research in Sweden: The Co-operation between Civilian and Military Research, 1947 – 1972," SKI Report 02:18, May 2002.

[12] *Ibid.*

[13] N. Rydell, P. Blomberg and E. Ericsson, "Experience from the commissioning, the criticality experiments and the power operation of the Agesta nuclear power plant," *Proceedings of the Third International Conference on the Peaceful Uses of Atomic Energy, Volume 5, Nuclear Reactors-I. Gas-cooled and Water-cooled Reactors*, United Nations, New York, 1965

[14] Carl-Erik Wikdahl, "Marvikenreaktorn-ett industripolitiskt utvecklingsprojekt i otakt med tiden," SKI Rapport 2007:18, April 2007.

including an on-line refueling machine located *inside* the reactor's pressure vessel.[15] It would also use enriched uranium, which would have to be imported from the U.S. Peaceful use restrictions imposed by the U.S. would make it difficult to use this reactor for the production of plutonium for nuclear weapons.

In a separate effort, Sweden produced a design for a boiling water reactor which used light (ordinary) water as the coolant. Like all other LWRs, this design used enriched uranium which would have to be imported from the U.S. The design was similar to that of General Electric's boiling water reactors. In 1965 the first of these reactors, Oskarshamn 1, was ordered. With a thermal output of 1,375 MW, this reactor was the first full-scale nuclear power reactor in Sweden.

Sweden planned to produce weapon-grade plutonium for its nuclear weapons. A 1963 study considered using either plutonium that was 2.0% Pu 240 or plutonium that was 3.5% Pu 240.[16] However with the rise of LWRs in the Swedish nuclear power program, there was an interest in what could be achieved using reactor-grade plutonium. In November 1965 Torsten Magnusson, who was head of the Swedish nuclear weapon design effort, addressed this issue at a conference on nuclear weapon cores. He said:

> It is important in this situation to keep one's eyes on what could be done from a military technical viewpoint, through the use of ordinary reactor plutonium.
>
> A certain amount of energy could obviously be obtained from reactor plutonium (Pu 238) [sic] simply by making a plutonium lump, compressing it and letting whatever happens happen. The initiation itself cannot be controlled.
>
> We have studied the energies which could be achieved by using reactor-grade plutonium in this manner. The limit for what might be possible to extract is likely to be in the region of 1 kiloton. That is to say, in taking a lump of reactor plutonium and compressing it, it seems likely, no matter how big this lump is made, that you cannot get significantly more than 1 kiloton.
>
> If a strong reflector is laid on top of the material, this will have a tamping effect. In that situation, a few kilotons could be achieved.
>
> *But in either case, in the 1-kiloton range a probable possibility appears to exist for making nuclear cores with reactor plutonium as weapon material.*
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> *We wanted to show this example, above all, because of the conceivable opportunities that are hidden here.*[17] [Emphasis added]

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[15] P. H. Margen, L. Leine and R. Nilson, "The design of the Marviken boiling heavy-water reactor with nuclear superheat," *Proceedings of the Third International Conference on the Peaceful Uses of Atomic Energy, Volume 6, Nuclear Reactors-II. Fast Reactors and Advanced Concepts,* United Nations, New York, 1965.

[16] Thomas Jonter, "Nuclear Weapons Research in Sweden: The Co-operation between Civilian and Military Research, 1947 – 1972," SKI Report 02:18, May 2002.

[17] Christer Larsson, "The History of a Swedish Atomic Bomb 1945-1972," *Ny Teknik,* No. 17, April 25, 1985, translation from U.S Foreign Broadcast Information Service.

It is clear that the man in charge of the Swedish nuclear weapon design effort did not consider the use of reactor-grade plutonium a show-stopper. It was realized that building a dedicated plutonium production reactor to produce weapon-grade plutonium was the preferred option but Sweden did not take this step any more than it built its own heavy water production or reprocessing facilities. Ultimately, the weapons usability of reactor-grade plutonium turned out to be irrelevant since by the time Oskarshamn 1 started operation in 1972, Sweden had already signed the Non Proliferation Treaty in 1968 and ratified it in 1970. Curiously Sweden conducted plutonium explosive compression tests into 1972. Due to uncertainties about the workability of some of its unique features and having been leap-frogged by Oskarshamn 1, Marviken was completed but never put into operation. Agesta was shut down in 1972 as being uneconomic.

Even before Oskarshamn 1 had been completed, Sweden began ordering additional LWRs and by the mid-1970s, 12 reactors were on order, under construction or in operation. A committee (the Aka committee) was formed to address the issue of nuclear waste. In its 1976 report the committee recommended that the spent fuel from these reactors be reprocessed and that Sweden should build its own reprocessing plant.[18] To avoid the obvious nuclear weapon implications of this decision, the committee claimed that the plutonium produced by Swedish LWRs was denatured:

> The plutonium which is produced in Swedish power reactors contains as much as 25 to 30% of plutonium-240. Such plutonium can only be utilized in weak and probably unreliable nuclear charges of highly questionable military value.[19]

This episode shows that, whether by ignorance or design, countries that are aware of the dangers of reactor-grade plutonium can still perpetuate the myth of denatured plutonium. At any rate, Sweden never built its own reprocessing plant and now prefers that spent LWR fuel be directly disposed of without reprocessing.

The bottom line is that the Swedish nuclear weapon effort planned to produce weapon-grade plutonium using natural uranium fueled heavy water reactors. However, when it became clear that such reactors would not be feasible under the constraints of the Swedish nuclear power program and that the emphasis had shifted to LWRs producing reactor-grade plutonium, the Swedish nuclear weapon design effort did not end. Rather the Swedish program correctly calculated that nuclear weapons with yields in the low kilotons could still be produced. Sweden's head of its nuclear weapon design effort considered using reactor-grade plutonium for the cores of nuclear weapons "a probable possibility."

Pakistan's Nuclear Weapon Program

In early 1972 in the aftermath of its defeat in the 1971 Indo-Pakistan War that led to Bangladesh's independence, Pakistan embarked on a nuclear weapon program. Like all countries developing nuclear weapons, the main requirement for such an effort was to acquire

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[18] "Spent nuclear fuel and radioactive waste," A summary of a report given by the Swedish government committee on radioactive waste, SOU 1976:32, Stockholm, 1976.
[19] *Ibid*., p. 43.

the nuclear material needed for the weapons and Pakistan initially appears to have chosen plutonium. A key step in the Pakistani program was to negotiate with France for a large-scale reprocessing plant. Pakistan signed the initial contract with France in March 1973 and the final contract on October 18, 1974.

A question that is seldom asked in the accounts of Pakistan's nuclear weapon program is what spent fuel was Pakistan planning to reprocess in this plant? Since at that time Pakistan had only one source of spent fuel, the KANUPP nuclear power plant, the obvious answer is that Pakistan planned to violate safeguards, reprocess the spent fuel from this reactor and use the resulting reactor-grade plutonium to produce nuclear weapons. However this obvious conclusion is often either ignored or met with denial.

For example, Feroz Hassan Khan, the former director of Pakistan's nuclear Strategic Plans Division, has cited various Pakistani sources who claim that Pakistan would never have violated safeguards on KANUPP to produce nuclear weapons but would have only have used indigenous facilities.[20] But what were Pakistan's options? A 1978 U.S. intelligence study correctly outlined the three possibilities.[21]

First, Pakistan could build its own plutonium production reactor. However there is no evidence that Pakistan either planned to or had the capability to build its own plutonium production reactor in the 1970s. Pakistan did eventually build such a reactor but it did not start operation until 1998. It is a heavy water moderated plutonium production reactor that required Pakistan to first build a heavy water production plant. Khan claims that Pakistan built the heavy water production plant without foreign design assistance but given the great difficulties India first experienced setting up its own heavy water production plants, Khan's assertion is implausible.[22] Indeed, an unanswered question regarding Pakistan's nuclear weapon program is the source of the foreign assistance for this facility.

Second, Pakistan could produce its own fuel bundles for KANUPP and from this fuel acquire plutonium free from safeguards. In the early years of the reactor's operation, this was not possible as Pakistan could not manufacture fuel for KANUPP. Instead Canada was supplying all of the reactor's fuel. However, it was only for this reason that there were safeguards at the reactor. This is to say the reactor was not under IAEA safeguards, only the Canadian fuel was. Therefore if Pakistan could produce fuel for KANUPP, it would not be under safeguards.

Due to Canada's cutoff of nuclear assistance to Pakistan at the end of 1976, Pakistan was actually forced to follow this path and manufacture its own fuel bundles for KANUPP. But this experience demonstrates that this path was not a feasible method for Pakistan to acquire weapon-grade plutonium. It was not until 1980 that Pakistan was able to produce a small quantity of reactor fuel and the rate of fuel production was low during the first half of the 1980s. It was not until 1986 that the rate of fuel production allowed the reactor to start operating at a capacity

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[20] Feroz Hassan Khan, *Eating Grass: The Making of the Pakistani Bomb*, Foundation Books, New Delhi, 2013, pp. 192-194.
[21] "Proliferation Group Quarterly Report, January-March 1978," Lawrence Livermore Laboratory, June 1978, formerly TOP SECRET, unclassified with redactions.
[22] Gary Milhollin, "Dateline New Delhi: India's Nuclear Cover-Up," *Foreign Policy*, Fall 1986.

factor of higher than 20% and not until 1990 that the last of the Canadian provided fuel was removed from the reactor.[23] Further this fuel was used in a manner to achieve high burnup so as to conserve the limited supply. Thus even if this had been Pakistan's plan, it would have still only acquired reactor-grade plutonium. The production of weapon-grade plutonium would have required the manufacture of roughly five times as much fuel, something clearly beyond Pakistan's capability. As it is, even with Pakistani fuel, the reactor has continued under IAEA safeguards.

Third, Pakistan could violate safeguards and use the plutonium contained in the KANUPP spent fuel. This is clearly the only option that could have provided Pakistan with plutonium for nuclear weapons before the 1990s. But could this plutonium have been weapon-grade rather than reactor-grade? The answer is no. As described above, Canada was providing the fuel for the reactor and would have noticed the large increase in fuel consumption that would have attended the production of weapon-grade plutonium. Further, the burnup of the KANUPP spent fuel has been published and one can calculate that the plutonium was mostly reactor-grade with a small amount of fuel-grade.

The KANUPP nuclear power plant is a CANDU type reactor with a design thermal output of 457 MW. Its design total electricity production is 137 MW. Subtracting the 12 MW required to operate the reactor, its design net electrical output is 125 MW. The plant started commercial operation on December 7, 1972 and began to be refueled on June 14, 1973. By the end of 1973 it had discharged 2.75 metric tons of uranium in spent fuel, which had an average burnup of 4,600 megawatt-days per metric ton (MWD/Te).[24] The spent fuel would have contained about eight kilograms of plutonium with a Pu 240 content of about 18%. This would have been fuel-grade plutonium, almost reactor-grade.

U.S. intelligence incorrectly estimated that KANUPP could produce 60 to 120 kilograms of plutonium per year. However, this estimate failed to take account of KANUPP's low capacity factor. Despite being a one-third scaled down version of the CANDU prototype (Douglas Point), KANUPP produced more electricity than could be absorbed by the small Pakistani grid especially at night and on weekends. As a result the reactor was forced to operate at a reduced capacity and KANUPP actually produced about 40 kilograms of plutonium per year in its early years.

Between the beginning of 1974 and April 1977 when Pakistan began to take steps to conserve reactor fuel, the average fuel burnup was 6,561 MWD/Te.[25] For the years 1974 through 1976, KANUPP would have discharged roughly 120 kilograms of plutonium and its Pu 240 content would have been about 23%, making it reactor-grade.

Khan has incorrectly claimed that it was the cutoff of Canadian fuel in 1976 that led KANUPP to produce low burnup spent fuel (what Khan calls "slow burned"). Actually the opposite is true.

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[23] Muhammad Salim, Iqbal Ahmed, Parvez Butt, "Experience in the Manufacture and Performance of CANDU Fuel for KANUPP."
[24] R. J. Graham, J. E. S. Stevens, "Experience with CANDU Reactors Outside of Canada, KANUPP, Karachi, Pakistan, RAPP, Rajasthan, India," CNA-74-203.
[25] Muhammad Salim, Iqbal Ahmed, Parvez Butt, "Experience in the Manufacture and Performance of CANDU Fuel for KANUPP."

When the reactor first started operation, the reactor operated with a flux flattened central zone in order to produce the design power output. In 1977, to conserve fuel and increase burnup, the flux in the central zone was allowed to peak. While the reactor operated in this fashion, the average spent fuel burnup increased to almost 8,000 MWD/Te and the resulting plutonium would have contained 26% Pu 240.[26] The price for this increased burnup was to lower the reactor electrical output from 137 MW to 105 MW. From 1986 to 1990 as the supply of Pakistani produced fuel began to increase, some flattening was restored and the power level increased to 112 MW. It was later increased to 120 MW but is now limited to less than 100 MW due to the deterioration of the reactor, which is scheduled to be permanently shut down in 2019.

Due to pressure from the U.S., France began to delay the sale of the reprocessing plant and eventually cancelled it in 1978, though Pakistan may have acquired some important technical information in the process. At the same time, Pakistan began to develop centrifuge enrichment using technology stolen from the Netherlands. By the late 1980s, Pakistan had produced its first nuclear weapon using highly enriched uranium. As was discussed above, in 1998, Pakistan's first plutonium production reactor went into operation. By about 2000 Pakistan would have produced and separated its first plutonium for nuclear weapons.

None of this should be allowed to obscure the main point. If Pakistan had acquired a reprocessing plant from France, Pakistan was fully prepared to violate the safeguards on the KANUPP spent fuel and use the plutonium from this reactor to produce nuclear weapons. This plutonium would have been reactor-grade with a Pu 240 content of about 23%.

India's Nuclear Weapon Program

Unlike both Sweden and Pakistan, for whom the option of using reactor-grade plutonium in nuclear weapons has likely long passed, India has taken steps to ensure that it currently has the option of using reactor-grade plutonium in its nuclear weapons. Further, there is some possibility that India has already deployed nuclear weapons which use reactor-grade plutonium.

As part of the 2006 India-U.S. nuclear deal, India pledged to place its "civilian" nuclear facilities under IAEA safeguards. India exempted eight nuclear power reactors from the list of civilian facilities. This is somewhat surprising since India already had two natural uranium fueled, heavy water moderated, plutonium production reactors (CIRUS and Dhruva which are termed "research reactors"). However this 2006 exchange between science journalist Pallava Bagla and Anil Kakodkar, chairman of India's Atomic Energy Commission is illuminating:

> Bagla: Is your strategic need for plutonium not met by CIRUS and Dhruva? Do you need additional capacity from civilian reactors?
> Kakodkar: "Yes, very clearly. Not from civilian reactors, but from power reactors."[27]

[26] *Ibid.*
[27] "India ratifies an additional protocol and will safeguard two more nuclear power reactors," International Panel of Fissile Materials Blog, July 1, 2014.

This statement characterizes these eight power reactors as military and not civilian. At first glance, it is not clear why India has taken this step since using nominal production figures, I will illustrate that CIRUS and Dhruva should have produced more than enough weapon-grade plutonium for India's nuclear weapon program.

CIRUS was provided to India by Canada and was a copy of Canada's NRX reactor. As part of the 1958 paper describing CIRUS, the Canadians pointed out that one of the four purposes of the NRX reactor was "the production of plutonium."[28]

CIRUS had a nominal thermal power output of 40 MW and began sustained operation in the early 1960s. By 1965 India had already produced plutonium metal using material derived from this reactor[29] and it also provided the plutonium for India's 1974 "peaceful nuclear explosive." The reactor was shut down for refurbishing between 1997 and 2002 and as part of the terms of the 2006 India-U.S. nuclear deal, the reactor was permanently shut down at the end of 2010.

Dhruva has a nominal thermal power output of 100 MW. It was constructed by India and began sustained operation in 1988. It is still in operation today.

Using nominal numbers for reactor operating time and plutonium production, Dhruva should produce about 20 kilograms of weapon-grade plutonium per year and CIRUS about 8 kilograms.[30] Assuming Dhruva has operated for 27 years[31] and CIRUS operated 42 years over its lifetime, this would result in a total production of 876 kilograms of separated weapon-grade plutonium. Assuming that 131 kilograms has been consumed by nuclear testing and other operations[32] a net total weapon-grade plutonium stockpile of 745 kilograms would remain. Assuming 5 kilograms of plutonium per weapon, this stockpile would be sufficient to produce 149 nuclear weapons, more than enough given the nominal estimates of 110 to 120 nuclear weapons in India's arsenal.[33]

However, for many years there have been indications that these two reactors' capacity factors were not nearly as high as the nominal calculations assume. Buried in a number of India's Department of Atomic Energy's Annual Reports are the quantities of fresh fuel provide to these reactors. If Dhruva were to operate at the 68.4% capacity factor that I assumed, then the reactor would require about 20.8 metric tons of fresh fuel per year.[34] However for the four years for which data was provided (Annual Reports for the years 2004-2005, 2006-2007, 2009-2010 and 2011-2012) only an average of 9.4 metric tons of fresh fuel was provided each year. This

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[28] R. D. Sage, D. D. Stewart, H. B. Prasad and H. N. Sethna, "Canada-India Reactor," Papers Presented by Canada-India to the Second International Conference on the Peaceful Uses of Atomic Energy, Geneva, Switzerland, September 1-13, 1958, P-1704. It is a measure of the lax thinking of the time that Canada saw no nuclear weapon dangers in providing CIRUS to India.

[29] Shri N. Srinivasan, "Fuel Reprocessing-The Initial Years," IANCAS Bulletin, July 1998.

[30] Assuming 250 days of operation per year (68.4% capacity factor), 0.8 kilograms of plutonium produced per 1,000 MWDs of operation, and plutonium 6% Pu 240.

[31] 1988 through 2015, assuming that the more recent fuel discharges have not yet been reprocessed.

[32] Zia Mian, A. H. Nayyar, R. Fajaraman and M. V. Ramana, "Fissile Materials in South Asia and the Implications of the U.S.-India Nuclear Deal," *Science and Global Security*, Vol. 14, 2006, p. 123.

[33] Hans M. Kristensen and Robert S. Norris, "Indian Nuclear Forces, 2015," *Bulletin of the Atomic Scientists*, Vol. 71, 2015.

[34] Assuming a fuel burnup of 1,200 MWD/Te to produce plutonium with a Pu 240 content of 6%.

implies a capacity factor of 31 percent, which would mean that Dhruva would only produce about 9 kilograms of plutonium per year instead of 20.

India recently confirmed Dhruva's poor performance.[35] For almost all of its operating life it never had a sustained power level of more than 50 to 60 MW. The 53 percent capacity factor that the reactor achieved in 2014 was its highest ever.

Similar data for CIRUS reveals a capacity factor of about 40 percent and an annual plutonium production rate of 4.7 kilograms. Using these revised annual plutonium production rates for these two reactors results in a total gross plutonium production of 440 kilograms and a net plutonium production of 309 kilograms. This amount of plutonium is only sufficient for about sixty-two nuclear weapons. It is possible that India's nuclear weapon arsenal is significantly smaller than is generally assumed but if it is not then India has manufactured up to half of its nuclear arsenal using plutonium produced in its unsafeguarded nuclear power reactors.

Could these unsafeguarded power reactors have produced large amounts of weapon-grade plutonium? The answer is no.

India's nuclear power reactors use a two-zone burnup configuration.[36] The inner 78 fuel channels have a target exit burnup of 10,000 MWD/Te and the outer 228 fuel channels have a target burnup of 5,500 MWD/Te. This produces an average burnup of about 6,650 MWD/Te and plutonium that is about 24% Pu 240. Even the 5,500 MWD/Te fuel has a Pu 240 content of about 20%.

It would have been difficult for India to produce large amounts of weapon-grade plutonium in its unsafeguarded nuclear power reactors. Until recently, India had a shortage of uranium and the production of weapon-grade plutonium requires about five times as much fuel as compared to the normal operation of the reactor.

Separating the weapon-grade plutonium would also pose a problem. The Trombay reprocessing plant where India produces all of its weapon-grade plutonium cannot process the uranium oxide fuel used in India's nuclear power reactors. Reprocessing the oxide fuel in one of India's plants which handle power reactor spent fuel would result in the plutonium being comingled with reactor-grade plutonium, unless the reprocessing plant were first shutdown and completely flushed out.

Therefore there is a distinct possibility that India has produced up to half its nuclear arsenal using reactor-grade plutonium. At the very least, the low plutonium production from Dhruva and CIRUS makes it clear as to why India has preserved the option of using reactor-grade plutonium in nuclear weapons by exempting eight of its nuclear power reactors from IAEA safeguards.

[35] "Operation of Dhruva Reactor at Rated Power of 100 Mw on Sustained Basis," BARC Newsletter, March-April 2016.
[36] S. S. Bajaj and A. R. Gore, "The Indian PHWR," *Nuclear Engineering and Design*, 2006.

Conclusions

When faced with the option of either shutting down their nuclear weapon programs or using reactor-grade plutonium, both Sweden and Pakistan chose to use reactor-grade plutonium. Sweden's head of its nuclear weapon design effort considered using reactor-grade plutonium for the cores of nuclear weapons "a probable possibility." Pakistan's only source of spent fuel to be processed in the reprocessing plant that it attempted to purchase from France in mid-1970s was its KANUPP power reactor. Published burnup figures show that the plutonium produce by KANUPP was reactor-grade. That neither country eventually produced nuclear weapons from reactor-grade plutonium should not be allowed to obscure these facts.

India has access to weapon-grade plutonium but the poor performance of its two plutonium production reactors has resulted in a plutonium stockpile that is significantly smaller than is generally assumed. This fact explains why India has retained the option of using reactor-grade plutonium in its nuclear arsenal by declaring eight of its nuclear power reactors to be military and not civilian. India's nuclear arsenal may be significantly smaller than is generally assumed but if it is not then India has already used reactor-grade plutonium to produce up to half of its nuclear stockpile.