Gregory S. Jones[1]
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Pakistan's Nuclear Material Production for Nuclear Weapons

Several sources have provided estimates of the amount of nuclear material that Pakistan may have produced for use in nuclear weapons.[2] These estimates have not accounted for the tritium that Pakistan is likely producing in its plutonium production reactors and in any case, need updating. Further Sundaresan and Ashok have claimed that Pakistan's limited supplies of natural uranium will restrict how much nuclear material Pakistan can produce.[3] In particular they have asserted that with the construction and operation of the four plutonium production reactors at Khushab, Pakistan will need to greatly restrict any additional highly enriched uranium (HEU) production.

This paper will produce new estimates of Pakistan's nuclear material stocks. Given what little is known about Pakistan's plutonium production reactors and uranium enrichment facilities, the range of uncertainty is large enough such that estimates that incorporate this full range are of little value. Instead, this paper will generate reasonable "mid-range" estimates of what nuclear material Pakistan might have and calculate the amount of natural uranium required to have produced this material.

Specifically, Pakistan could have produced about 3.0 metric tons of HEU, about 330 kilograms of plutonium and about 690 grams of tritium by the end of 2020. This would be enough nuclear material to produce about 250 nuclear weapons and enough tritium to boost over 100 weapons. By the end of 2025 Pakistan could have a total of 3.5 metric tons of HEU, 510 kilograms of plutonium and 1,060 grams of tritium. This would be enough nuclear material to produce a total of around 300 nuclear weapons and enough tritium to boost about 160 weapons.

The size of Pakistan's nuclear arsenal is more likely constrained by delivery systems rather than nuclear material availability and Pakistan very likely has fewer nuclear weapons than these nuclear material estimates would indicate. The amount of natural uranium required to produce this nuclear material does not appear to have been a serious constraint in the past and is unlikely to be one in the future.

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[1] This paper is the product of the author's personal research and the analysis and views contained in it are solely his responsibility. Though the author is also a part-time adjunct staff member at the RAND Corporation, this paper is not related to any RAND project and therefore RAND should not be mentioned in relation to this paper. I can be reached at GregJones@proliferationmatters.com

[2] David Albright, "Pakistan's Inventory of Weapon-Grade Uranium and Weapon-Grade Plutonium Dedicated to Nuclear Weapons," Institute for Science and International Security, October 19, 2015 https://isis-online.org/uploads/isis-reports/documents/Pakistan_WGU_and_WGPu_inventory_Oct_16_2015_final_1.pdf and "Global Fissile Material Report 2015: Nuclear Weapon and Fissile Material Stockpiles and Production," International Panel on Fissile Material, 2015. http://fissilematerials.org/publications/2015/12/global_fissile_material_report_7.html A table on the International Panel on Fissile Material website provides an updated estimate as of the end of 2018 but without any supporting analysis.

[3] Lalitha Sundaresan and Kaveri Ashok, "Uranium constraints in Pakistan: how many nuclear weapons does Pakistan have?," *Current Science*, Vol. 115, No. 6, 25 September 2018. https://www.currentscience.ac.in/Volumes/115/06/1042.pdf

This paper will first estimate how much plutonium and tritium the four reactors at Khushab may have generated in the past and their current production rates. Next the paper will look at the operation of the KANUPP-1 nuclear power reactor. At one time, Pakistan appeared to be poised to use the reactor-grade plutonium produced by this reactor for its nuclear weapon program.[4] It does not appear that Pakistan ever took this step as the theft of centrifuge uranium enrichment technology provided other options. However, since 1980, Pakistan has provided the natural uranium needed to fuel this reactor, so the amount of this fuel through to the present day is calculated. Next the production of HEU by Pakistan's enrichment plants is examined. Additionally, the amount of HEU consumed in Pakistan's 1998 nuclear tests is discussed. Finally, the overall results and conclusions are presented.

Khushab Reactors

Pakistan has built four heavy water moderated plutonium production reactors near Khushab. Little is known about these reactors, including their power levels, operating capacity factors, fuel burnup, and whether any or all of these reactors are also producing tritium. There is general agreement only as to the years each reactor started high-power operation: for Khushab-1, 1998; Khushab-2, 2010; Khushab-3, 2012 and Khushab-4, 2015.

David Albright, of the Institute for Science and International Security, has produced various estimates for the power level of these reactors. His initial estimate for Khushab-2 was a very implausible 1,000 MW.[5] More recently he has published much lower and more reasonable estimates.[6] To calibrate Albright's various estimates, I assume that Khushab-1 was a copy of India's Cirus reactor with a 40 MW power, something that has been suggested by scientific papers published by Pakistani scientists.[7] Then based on Albright's analysis: Khushab-2 would also have a 40 MW power; Khushab-3, 50 MW and Khushab-4, 80 MW.[8]

Elsewhere I have argued against estimates of the upgraded power level of the Dimona plutonium production reactor in Israel being as high as 150 MW, since this would require significant

[4] Gregory S. Jones, *Reactor-Grade Plutonium and Nuclear Weapons: Exploding the Myths*," Nonproliferation Policy Education Center, 2018, pp. 110-115. https://nebula.wsimg.com/3fd1e3cfbbf101d6c4f562e17bc8604c?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1

[5] David Albright and Paul Brannan, "Commercial Satellite Imagery Suggests that Pakistan is Building a Second, Much Larger Plutonium Production Reactor: Is South Asia Headed for a Dramatic Buildup in Nuclear Arsenals?," Institute for Science and International Security, July 24, 2006. https://isis-online.org/publications/southasia/newkhushab.pdf

[6] David Albright, Sarah Burkhard, Claire Chopin and Frank Pabian, "New Thermal Power Estimates of the Khushabl Nuclear Reactors," Institute for Science and International Security, May 23, 2018. https://isis-online.org/uploads/isis-reports/documents/Khushab_Reactor_Power__23May2018_Final.pdf

[7] M.J. Khan, Aslam, N. Ahmad, "Neutronics analyses of natural uranium fueled, light water cooled, heavy water moderated and graphite reflected nuclear reactors," *Annals of Nuclear Energy*, Vol. 31, 2004. https://www.sciencedirect.com/science/article/pii/S0306454904000593?via%3Dihub

[8] David Albright, Sarah Burkhard, Claire Chopin and Frank Pabian, "New Thermal Power Estimates of the Khushab Nuclear Reactors," Institute for Science and International Security, May 23, 2018, p. 8. Given the uncertainties, I round to the nearest ten.

changes in the reactor's fuel design and refueling method.[9] My set of estimates for the power level of the four Pakistani reactors keeps the power level of the Khushab-4 reactor reasonably low. Note what really matters is the total power level of the four reactors, which for my estimates is 210 MW. Other have assumed that the four reactors each have a power of 50 MW for a total of 200 MW. In this case, the results as far as plutonium production is concerned will be only 5% different.

If the reactors at Khushab produce only plutonium, then natural uranium fuel can be used. Most estimates of Pakistani plutonium production assume a fuel burnup of 1,000 megawatt-days per metric ton (MWD/MT). This would produce plutonium with a Pu-240 content of 5%.[10] Significant uranium saving can be achieved by producing plutonium with a Pu-240 content of 6%, since the fuel burnup could then be 1,200 MWD/MT. Plutonium with a 6% Pu-240 content is standard U.S. weapon-grade plutonium. At this burnup, a heavy water moderated reactor would produce about 0.8 kilograms of plutonium per 1,000 MWDs of operation.

There are indications that Pakistan may have developed boosted nuclear weapons, perhaps with foreign assistance. Since 2005 Pakistan has tested two cruise missiles (the Babur/Hatf-7 and the Ra'ad/Haft8) and since 2011 it has tested two short-range ballistic missiles (Abdali/Hatf-2 and Nasr/Hatf-9). Pakistan has described these missiles as "nuclear capable," but the low payload and small diameters of these missiles would seem to rule out the use of pure fission implosion weapons. This raises two possibilities. First, Pakistan is bluffing and is just conveniently applying the label "nuclear capable" to every missile regardless of whether it actually is. Second, Pakistan has developed small, lightweight boosted fission weapons.

To produce the tritium required to manufacture boosted nuclear weapons, countries irradiate lithium in nuclear reactors.[11] Natural uranium-fueled reactors have only a limited amount of excess reactivity. Therefore, given the strong neutron absorbing characteristics of lithium, all reactors that have produced tritium have used enriched uranium. Due to their different masses, a gram of tritium is equivalent to 79.3 grams of plutonium. If a neutron that would have produced plutonium instead produces tritium, the lost mass of plutonium is 79.3 times as much as the tritium produced. However, work at Hanford showed that some tritium could be produced by using neutrons that were otherwise wasted by escaping from the reactor or were absorbed in reactor structural materials. Therefore, the actual reduction in plutonium production was somewhat less.

Calculations performed at Hanford state that for 1.0% enriched fuel, a reactor would produce about 0.67 kilograms of plutonium per 1,000 MWD of operation and the plutonium equivalent of 0.23 kilograms of tritium per 1,000 MWD of operation.[12] To produce plutonium with a Pu-240

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[9] Gregory S. Jones, "Estimating Israel's Stocks of Plutonium, Tritium and HEU," September 18, 2018, pp. 1-2. https://nebula.wsimg.com/af67c5952110bc7a05f250260765c792?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1

[10] M.J. Khan, Aslam, N. Ahmad, "Neutronics analyses of natural uranium fueled, light water cooled, heavy water moderated and graphite reflected nuclear reactors," *Annals of Nuclear Energy*, Vol. 31, 2004, p. 1350.

[11] Contrary to wide-spread belief, this lithium need not be enriched. See: Gregory S. Jones, "Estimating Israel's Stocks of Plutonium, Tritium and HEU," September 18, 2018, p. 4.

[12] "Hanford Reactor and Separations Facility Advantages," HW-78100, Hanford Atomic Products Operation, Richland, Washington, June 27, 1963, p. 20. The Hanford calculations assume that 0.83 kilograms of plutonium are

content of 6%, the fuel would have a burnup of about 1,600 MWD/MT. Increasing the enrichment of the fuel would decrease the amount of plutonium produced and increase the amount of tritium. For 1.2% enriched fuel, the reactor would produce about 0.61 kilograms of plutonium per 1,000 MWD of operation and the plutonium equivalent of 0.33 kilograms of tritium per 1,000 MWD of operation.

For my estimate I make the following assumptions. The Khushab-1 reactor has only produced plutonium and uses natural uranium fuel with a burnup of 1,200 MWD/MT. The other three reactors have been combined plutonium/tritium producers since their start of operations. To provide adequate stocks of plutonium, these three reactors use 1.0% enriched fuel with a burnup of 1,600 MWD/MT. All reactors operate for 250 days per year, they started initial operation at the beginning of their start years, there is a two year lag in plutonium production to allow for irradiation, cooling and reprocessing of the fuel and a one year lag in the production of tritium.

With these assumptions, at the end of 2020 Pakistan will have accumulated 330 kilograms of separated weapon-grade plutonium and 690 grams of tritium. This latter estimate accounts for tritium's decay since the start of production.[13] Assuming 0.3% enrichment tails in the production of the 1.0% enriched fuel, Pakistan will have used 540 metric tons of natural uranium to operate these reactors by the end of 2020.

Each year the reactors will produce 36.5 kilograms of plutonium, 125 grams of tritium and consume 54 metric tons of natural uranium. It would take about 7,000 SWU per year to produce the required 1.0% enriched fuel. By 2025 Pakistan will have accumulated 510 kilograms of plutonium and 1,060 grams of tritium.

KANUPP-1

Canada provided Pakistan with a small CANDU type reactor, called KANUPP-1. It started commercial operation in 1972 and initially Canada supplied the fuel for this reactor. In the aftermath of India's "peaceful" nuclear explosion in 1974, Canada demanded that Pakistan formally renounce any effort to acquire nuclear weapons. When Pakistan refused, Canada cutoff the fuel supply to KANUPP-1 at the end of 1976. Pakistan initially took steps to stretch the remaining supply of Canadian fuel and eventually fabricated fuel for the reactor using uranium for its own sources.

A Pakistani paper states that through 2012 KANUPP-1 had operated the equivalent of 5,060 full power days (FPD).[14] The first 1,019 FPDs used Canadian fuel, so the remaining 4,041 FPDs

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produced in natural uranium fuel per 1,000 MWD of operation. I have scaled these results for a reactor that produces only 0.80 kilograms of plutonium in natural uranium fuel per 1,000 MWD of operation. To convert tritium production from plutonium equivalent to actual grams of tritium, divide by 79.3. https://www.osti.gov/servlets/purl/10184818

[13] If tritium is produced at a constant annual rate of A, then the buildup of tritium over time is found by the formula: $(A/\lambda) \times (1 - e^{-\lambda t})$. λ is the decay constant of tritium, which is the natural logarithm of 2 divided by the half-life of tritium (0.6931/12.32 years = 0.05626 yr^{-1}).

[14] F. Tasneem and S. E. Abbasi, "Fuel Integrity Assessment at KANUPP," *Pressurized Heavy Water Reactor Fuel: Integrity, Performance and Advanced Concepts*, Proceedings of the Technical Meetings Held in Bucharest, 24-27 September 2012, and in Mumbai, 8-11 April 2013, IAEA-TECDOC-CD-1751, International Atomic Energy

used Pakistani fuel.[15] The reactor's thermal power output was 457 MW. Thus, through the end of 2012, the reactor had produced about 1,850,000 MWDs using Pakistani provided fuel. Since the average fuel burnup during this time interval was 7,400 MWD/MT, the total uranium consumption was about 250 metric tons.

After 2012 there were a number of changes to the reactor. For safety reasons the reactor power level was derated to 337 MW and between 2013 and 2018 the average capacity factor was 43.9% (160 days per year).[16] During the 1980s, in order to stretch the supply of Canadian fuel, Pakistan burned the fuel to around 8,000 MWD/MT, at the cost of needing to lower the reactor's power level.[17] In the 1990s Pakistan lowered the goal for fuel burnup to about 6,600 MWD/MT. However, data shows that this level of fuel burnup has not always been achieved.[18] To be conservative, I assume a fuel burnup of 6,000 MWD/MT. Therefore, the reactor would use about nine metric tons of uranium per year and a total of 63 metric tons in the six years 2013-2018.

Various Pakistani sources have suggested that KANUPP-1 would be permanently shut down some time in the 2019-2022 time span due to the reactor's age. The reactor has not yet been formally shut down but it appears that in reality it has. The reactor's capacity factor in 2019 was only 4.9% (requiring 1 metric ton of uranium fuel) and it did not operate in 2020. Summing up, the reactor would have used 314 metric tons of uranium between 1980 and 2019.

HEU Production

There are significant uncertainties as to how much HEU Pakistan may have produced since little specific is known about Pakistan's enrichment facilities. It is generally thought that Pakistan's enrichment facilities have an enrichment output in the low 10,000s SWU (separative work units). How much HEU this amount of enrichment would produce depends on how efficiently Pakistan operates it centrifuge enrichment facilities (See Appendix). Pakistan first began producing HEU in the 1980s. It has likely expanded and improved these facilities over time but it also probably started producing some low enriched uranium to fuel the reactors at Khushab to facilitate tritium production. A reasonable estimate is that Pakistan has produced roughly 100 kilograms of HEU

Agency, Vienna, 2014, p.61. https://www-pub.iaea.org/MTCD/Publications/PDF/TE_1751_CD/PDF/Tecdoc-1751.pdf

[15] *Ibid*., p. 63.

[16] International Atomic Energy Agency, Power Reactor Information System, KANUPP-1. https://pris.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current=427

[17] To achieve full power, it is necessary to lower the power level in the central part of the reactor, which is known as "flattening." Flattening lowers the burnup of the fuel. During the 1980s Pakistan allowed the power level in the central part of the reactor to peak. To prevent the fuel in the central part of the reactor from becoming too hot it was necessary to lower the reactor's power level. Since the 1990s, Pakistan is again flattening the reactor's power distribution. See: Muhammad Salim, Iqbal Ahmed, Parvez Butt, "Experience in the Manufacture and Performance of CANDU Fuel for KANUPP," *4th International Conference on CANDU Fuel*, 1995, October 1-4, Pembroke, Canada, p.1-48. https://inis.iaea.org/collection/NCLCollectionStore/_Public/30/000/30000471.pdf?r=1

[18] S. E. Abbasi and T. Fatima, "Enhancement in the Storage Capacity of KANUPP Spent Fuel Storage Bay," *Management of Spent Fuel from Nuclear Power Reactors*, Proceeding of an International Conference Organized by the International Atomic Energy Agency in Cooperation with the OECD Nuclear Energy Agency and Held in Vienna, Austria, 31 May-4 June 2010, International Atomic Energy Agency, Vienna, 2015, Session 10, p. 51. https://www.iaea.org/publications/13488/management-of-spent-fuel-from-nuclear-power-reactors

per year which is likely continuing. This production would require 21.8 metric tons of natural uranium feed per year (0.3% tails) and depending on the efficiency of the Pakistani enrichment facilities around 20,000 to 30,000 SWU per year. Given that Pakistan's initial production rate was probably significantly lower than 100 kg of HEU per year, Pakistan's production to date is likely around 3 metric tons which would have required about 650 metric tons of natural uranium to produce.

HEU Consumed in 1998 Nuclear Tests

On May 11, 1998, India announced that it had conducted three nuclear tests, followed by the announcement that it conducted two more tests on May 13, 1998. In response, Pakistan announced that it conducted five nuclear tests on May 28, 1998, followed by another on May 30, 1998. Albright estimates that 90-120 kilograms of HEU were consumed by these six Pakistani tests.[19] A 2010 analysis by the International Fissile Material Panel, estimated that about 100 kilograms of HEU were consumed by these six tests.[20]

Seismic data from these tests raises doubts about the veracity of both the Indian and Pakistani announcements.[21] India claimed to have tested three devices on May 11 with a total yield of 55 kilotons. However, the seismic data is consistent with a single test with a body wave magnitude of 5.0, indicating a total yield of 9-16 kilotons. India claimed to have tested two devices on May 13 with a total yield of 0.8 kilotons but no seismic signal was detected even though one should have been if the yield claimed by India was correct.

Pakistan claimed that its five tests on May 28 had a total yield of 30-35 kilotons but the seismic signal had a body wave magnitude of 4.9, indicating a total yield of only 6-13 kilotons. Pakistan did not announce a yield for its test on May 30 but it had a body wave magnitude of 4.3, indicating a yield of 2-8 kilotons.

It seems likely that Pakistan tested only two devices in May 1998 and that its public announcements were simply an attempt to literally "one-up" India's announced test series. The two test devices would have consumed only about 40 kilograms of HEU. This amount is well within the uncertainty of my HEU estimate for Pakistan and therefore I do not explicitly account for it.

Conclusions: Nuclear Weapon Stockpile and Natural Uranium Requirements

Assuming 20 kilograms of HEU or 5 kilograms of plutonium are required per nuclear weapon, Pakistan's estimated stockpile of 3 metric tons of HEU and 330 kilograms of plutonium would be sufficient for about 220 unboosted nuclear weapons. Elsewhere I have estimated that should Pakistan have boosted nuclear weapons, each weapon would require 5 grams of tritium per

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[19] David Albright, "Pakistan's Inventory of Weapon-Grade Uranium and Weapon-Grade Plutonium Dedicated to Nuclear Weapons," Institute for Science and International Security, October 19, 2015, p. 8.

[20] *Global Fissile Material Report 2010*, International Fissile Material Panel, 2010, p. 126. http://fissilematerials.org/library/gfmr10.pdf

[21] Brian Barker et al., "Monitoring Nuclear Tests," *Science*, Vol. 281, No. 5385, September 25, 1998. https://science.sciencemag.org/content/281/5385/1967.full

weapon and that Pakistan would hold a five year reserve of tritium.[22] Given these assumptions, Pakistan's estimated stockpile of 690 grams of tritium would be sufficient to boost about 100 nuclear weapons. Further, the British have stated that boosting allows the amount of nuclear material in each weapon to be reduced while still maintaining or even increasing the yield.[23] Therefore Pakistan could have enough HEU and plutonium for at least 250 nuclear weapons, of which approximately 100 could be boosted.

Kristensen et.al. have estimated that in 2018, Pakistan's nuclear arsenal was no more than 140 to 150 weapons.[24] They have cogently argued that even if Pakistan possesses more nuclear material, nuclear delivery systems are the limiter on the size of its nuclear arsenal and I agree.[25] Nevertheless given Pakistan's paranoia regarding India and bureaucratic inertia, I expect Pakistan's stockpile of nuclear material to continue to grow at the current rate and by 2025 Pakistan could have 3.5 metric tons of HEU, 510 kilograms of plutonium and 1,060 grams of tritium. This would be sufficient for approximately 300 nuclear weapons, about 160 of which could be boosted. I do not expect Pakistan's arsenal to approach 300 nuclear weapons in the near term but it will continue to grow, especially in the number of boosted weapons.

As far as natural uranium requirements are concerned, to date Pakistan used 314 metric tons to fuel KANUPP-1 (which is now shut down), 654 metric tons to produce HEU and 540 metric tons to fuel the reactors at Khushab (most of the Khushab consumption occurred only in the last decade) for a total of about 1,500 metric tons. Given that this consumption was spread over 40 years, this is less than 40 metric tons per year, which was well within Pakistan's production capability. Going forward the requirements are somewhat higher as the reactors at Khushab require 54 metric tons of natural uranium per year and the production of HEU requires 22 metric tons of natural uranium per year, for a total of 76 metric tons per year. Pakistan can probably provide this quantity of natural uranium with little difficulty.

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[22] The requirement for a 5 year tritium reserve means that only 75.5% of Pakistan's tritium stockpile could actually be used in weapons. See: Gregory S. Jones, "Do India and Pakistan Possess Boosted Nuclear Weapons? Tritium Supply Considerations," July 31, 2019.
https://nebula.wsimg.com/b2c3c9b49ad062fdf2c7a52be054c98c?AccessKeyId=40C80D0B51471CD86975&disposition=0&alloworigin=1

[23] Lorna Arnold, *Britain and the H-Bomb*, UK Ministry of Defense, Palgrave, 2001, p.177.

[24] Hans M. Kristensen, Robert S. Norris and Julia Diamond, "Pakistani nuclear forces, 2018," *Bulletin of the Atomic Scientists*, Vol. 74, No. 5, 2018.
https://www.tandfonline.com/doi/pdf/10.1080/00963402.2018.1507796?needAccess=true

[25] *Ibid.*, p. 351.

Appendix

Possible Operating Modes of Pakistan's Centrifuge Enrichment Facilities: Implications for HEU Production and Natural Uranium Consumption

If Pakistan's centrifuge facilities were arranged to produce HEU from natural uranium in long ideal cascades, one can find, using a separative work calculator, that to produce 1 kilogram of HEU requires 193 SWU (separative work units) and 218 kilograms of natural uranium assuming 0.3% tails. However, Pakistan does not use long ideal cascades to produce HEU from natural uranium but rather has broken the process into four sets of shorter cascades.

The best description of this arrangement is a proposed plant that Pakistan designed for Libya.[26] The first set of cascades would produce 3.5% enriched uranium from natural uranium. The second set would produce 20% enriched uranium using the 3.5% enriched uranium as feed, the third 60% enriched uranium and the fourth 90% enriched uranium. The plant would use 5,832 centrifuges to produce about 100 kilograms of HEU per year.

There is no reason why this arrangement could not function as efficiently as long ideal cascades as long as the stripping sections of the second, third and fourth set of cascades have sufficient stages so that the tails produced have the same enrichment as the feed of the prior stage. (See Table 3) If the above Libyan design operated similar to an ideal cascade, then the plant would produce 19,300 SWU per year, with each centrifuge producing about 3.3 SWU per year. Albright assumes that each centrifuge produces 5 SWU per year and takes the difference between the actual performance and his estimate as an indicator that the use of four sets of cascades is inefficient.[27] Depending on how the tails are handled, the four sets of cascades arrangement could be inefficient but it could also be that Albright's estimate of the amount of SWU produced per centrifuge is too high.

It is certainly possible for the SWU utilization of an enrichment process to be inefficient since any mixing of uranium with different enrichments leads to a loss of SWU. However, since the U-235 in the uranium is never destroyed, it is always possible to recover the U-235 and the amount of natural uranium required can always be the same as that of an ideal cascade. This will be true even in a case where the stripping sections have too few stages to produce the feed of the prior stage, since the tails can always be diluted to the proper enrichment.

Take the following example: assume that the enrichment process is broken into four sets of cascades, each with the same number of enriching stages. In this case the first set would produce uranium with an enrichment of 4.1%, the second 20.2%, the third 60.2% and the fourth 90.0%. If the first set has a stripping section with enough stages to produce 0.3% tails and the stripping sections of the other three sets has this same number of stages, then the tails of the second set would be 1.76%, the third 9.6% and the fourth 38.9%.

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[26] David Albright, *Peddling Peril*, Free Press, New York, 2010, p. 123.
[27] David Albright, "Pakistan's Inventory of Weapon-Grade Uranium and Weapon-Grade Plutonium Dedicated to Nuclear Weapons," Institute for Science and International Security, October 19, 2015, pp. 5-6.

Table 1 shows the inefficiency if no use is made of the tails from the second, third and fourth sets of cascades. This process would require 835 kilograms of natural uranium and 557 SWU to produce one kilogram of HEU, rather than the 218 kilograms of natural uranium and 193 SWU required by an ideal cascade.

Table 1

Production of HEU Using Four Sets of Cascades
No Use Made of Tails From the Second, Third and Fourth Sets of Cascades

Set of Cascades	Product Enrichment and Quantity	Feed Enrichment and Quantity	Tails Enrichment and Quantity	SWU
Fourth	90.0% 1.0 kg	60.2% 2.4 kg	38.9% 1.4 kg	1.7
Third	60.2% 2.4 kg	20.2% 11.46 kg	9.6% 9.06 kg	7.23
Second	20.2% 11.46 kg	4.1% 90.31 kg	1.76% 78.85 kg	54.0
First	4.1% 90.31 kg	0.711% 834.98 kg	0.3% 744.67 kg	494
Total (Rounded)		Natural U 835 kg		557

This great inefficiency provides a substantial incentive to find some way to utilize the tails from the second, third and fourth sets of cascades. The simplest way to achieve this goal would be to dilute the tails from the third and fourth sets of cascades to produce feed for the second and third sets of cascades respectively and to dilute the tails from the second set of cascades to produce natural uranium (the feed of the first set of cascades). If one uses 1.34 kilograms of natural uranium, the 1.4 kilograms of tails from the fourth set of cascades can be diluted to produce 2.74 kilograms of 20.2% enriched uranium. Using this 2.74 kilograms of enriched uranium as part of the feed to the third set means that the amount of 20.2% enriched uranium that needs to be produced by the second set of cascades can be reduced from 11.46 kilograms to 8.72 kilograms. The amount of 1.76% enriched uranium produced as tails by the second set of cascades is reduced from 78.85 kilograms to 60.0 kilograms.

The reduction in the required amount of 20.2% enriched uranium from 11.46 kilograms to 8.72 kilograms in turn reduces the amount of 4.1% enriched uranium required as feed for the second set from 90.31 kilograms to 68.72 kilograms. Using 14.7 kilograms of natural uranium, the 9.06 kilograms of 9.6% tails produced by the third set of cascades can be diluted to produce 23.76 kilograms of 4.1% enriched uranium. This further reduces the amount of 4.1% enriched uranium that must be produced by the first set of cascades from 68.72 kilograms to 44.96 kilograms. The amount of depleted uranium produced as 0.3% tails by the first set of cascades is reduced from 744.67 kilograms to 370.73 kilograms. Finally, using 153.14 kilograms of the 0.3% tails, the

60.0 kilograms of 1.76% tails produced by the second set of cascades can be diluted to produce 213.14 kilograms of natural uranium (0.711% enriched). This process is shown in Table 2.

Table 2

Production of HEU Using Four Sets of Cascades
Tails From Second, Third and Fourth Sets of Cascades Diluted Using Natural or 0.3% Depleted Uranium

Set of Cascades	Product Enrichment and Quantity	Feed Enrichment and Quantity	Tails Enrichment and Quantity	SWU
Fourth	90.0% 1.0 kg	60.2% 2.4 kg	38.9% 1.4 kg	1.7
Third	60.2% 2.4 kg	20.2% 11.46 kg	9.6% 9.06 kg	7.23
Second	20.2% 8.72 kg	4.1% 68.72 kg	1.76% 60.0 kg	41.1
First	4.1% 44.96 kg	0.711% 415.69 kg	0.3% 370.73 kg	246
Total (Rounded)		Natural U 415.69 kg + 1.34 kg + 14.7 kg – 213.14 kg = 219 kg	0.3% 370.73 kg – 153.14 kg = 218 kg	296

As can be seen from the table, using the tails by diluting them with natural and 0.3% depleted uranium leads to a substantial improvement in efficiency. All of the U-235 is recovered so that this process using four sets of cascades requires no more natural uranium than does an ideal cascade (the difference between 218 kilograms and 219 kilograms is due to calculational rounding). A substantial amount of the separative work (SWU) is recovered as well as this process requires only 296 SWU instead of the 557 SWU that would be needed if the tails were not used. However, this is still about 50% higher than the 193 SWU required by an ideal cascade. With the process shown in Table 2, to produce 100 kilograms of HEU would require about 30,000 SWU and 21.8 metric tons of natural uranium.

The arrangement with four sets of cascades can be made to operate as efficiently as long ideal cascades by adding sufficient stages to stripping sections of the second, third and fourth set of cascades so that the tails produced have the same enrichment as the feed of the prior stage. It is believed that Pakistan may have expanded it enrichment facilities by adding additional centrifuges and it is possible that Pakistan has improved its enrichment facilities to match the performance of an ideal cascade. If so, then production of 100 kilograms of HEU would require only 19,300 SWU instead of the 30,000 SWU needed if the stripping sections are too short and the tails must be diluted. The amount of natural uranium required would still be 21.8 metric tons. Table 3 shows how this could be arranged.

In sum, assuming that the tails are utilized, the amount of natural uranium required to produce HEU using a four sets of cascades arrangement should be no higher than that of long ideal cascades. However, the amount of separative work required might be about 50% higher if the tails must be diluted to a lower enrichment. On the other hand, if the stripping sections of the second, third and fourth sets of cascades are long enough, the four sets of cascades arrangement might require no more SWU to produce HEU than would sets of long ideal cascades.

Table 3

Production of HEU Using Four Sets of Cascades
Stripping Sections of the Second, Third and Fourth Sets of Cascades Have Enough Stages So That Their Tails Can Be Used as Feed for the Prior Stage

Set of Cascades	Product Enrichment and Quantity	Feed Enrichment and Quantity	Tails Enrichment and Quantity	SWU
Fourth	90.0% 1.0 kg	60.2% 1.745 kg	20.2% 0.745 kg	2.2
Third	60.2% 1.745 kg	20.2% 6.08 kg	4.1% 4.34 kg	7.7
Second	20.2% 5.34 kg	4.1% 30.68 kg	0.711% 25.34 kg	39
First	4.1% 26.34 kg	0.711% 243.53 kg	0.3% 217.19 kg	144
Total (Rounded)		Natural U 243.53kg – 25.34 kg = 218 kg		193