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Exploring Uranium Resource Constraints on Fissile Material Production in Pakistan

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This paper evaluates possible scenarios for Pakistan's uranium enrichment and plutonium production programs since the late 1970s by using Pakistan's supply of natural uranium as a constraint. Since international sanctions have prevented Pakistan from importing uranium for decades, it has had to rely on domestic uranium production—currently estimated as approximately 40 tons a year. The paper divides the development of Pakistan's uranium enrichment and plutonium production programs into three broad periods: from the beginning in the late 1970s until the 1998 nuclear tests; from 1999 to the present; and from the present to 2020; and considers how Pakistan could allocate its domestic uranium between its uranium enrichment and plutonium production programs for each period. This assessment is completed for enrichment capacities ranging from 15,000 to 75,000 separative work units (SWU) and takes into account the construction of the second and third plutonium production reactors at Khushab. The study finds that Pakistan may have sufficient natural uranium to fuel the three reactors, if they are approximately 50 MWt each, but that for some of these enrichment capacities, there will be a shortfall of natural uranium by 2020. The paper considers the impact of alternative sources of enrichment feed such as depleted tails from previous enrichment activity and reprocessed uranium from low-burn-up spent fuel from the Khushab reactors. There are signs Pakistan early on may have enriched some reprocessed uranium, possibly acquired from China. It finds that by 2020, Pakistan could have accumulated approximately 450 kg of plutonium from the Khushab reactors and 2500–6000 kg of highly enriched uranium (HEU) (90 percent enriched) for enrichment capacities ranging from 15,000–75,000 SWU. These stocks would be sufficient for perhaps 100–240 simple fission weapons based on HEU and for 90 plutonium weapons. Pakistan may be able to produce more weapons if it either increases its rate of uranium mining or has more advanced weapon designs requiring less fissile material in each weapon.

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INTRODUCTION

Pakistan launched its nuclear research and development program in 1954, relying like many other countries on technical training and a research reactor offered by the United States as part of Atoms for Peace. The program now encompasses the whole nuclear fuel cycle, from uranium mining through uranium enrichment, fuel fabrication, nuclear reactor construction and operation, and the reprocessing of spent nuclear fuel to recover plutonium.

The civilian component of Pakistan's nuclear program, which is under International Atomic Energy Agency (IAEA) safeguards, consists of the 125 MWe Canadian supplied heavy water power reactor near Karachi (KANUPP) and a 300 MWe Chinese designed and built light water reactor at Chashma (CHASNUPP). A second reactor of the same design is currently under construction at Chashma.

At least since 1974, when India first tested a nuclear weapon, Pakistan's nuclear complex has had an overtly military component. Pakistan first tested its nuclear weapons in 1998; two weeks after India conducted a series of tests. Beyond this, there is limited official information in the public domain about Pakistan's nuclear weapons program. It is generally accepted that a uranium enrichment program was launched in the mid 1970s at Kahuta, and that Pakistan uses gas centrifuge technology to produce highly enriched uranium (HEU) for nuclear weapons. However, the number and capacity of the enrichment plants and the centrifuges that Pakistan uses, including the possible development of several generations of centrifuges, are quite uncertain with conflicting reports in the literature.

Similarly, it is widely accepted that Pakistan built and has been operating a production reactor at Khushab since the late 1990s to create plutonium for nuclear weapons. It is also building two additional production reactors at the same site, one of which is expected to begin operation in late 2009. Pakistan has not revealed, however, the design power of any of the Khushab reactors.

There is also little official information regarding other details of Pakistan's fuel cycle activities, such as uranium mining and milling, fuel fabrication, and reprocessing, all of which are unsafeguarded. In the absence of such information, one is required to rely on a combination of judgments by a handful of independent analysts and media reports, augmented by occasional statements from officials.

This article explores how Pakistan's limited domestic production of uranium may serve to constrain the size and possible evolution of its fissile material production capabilities and stockpiles. Since Pakistan does not publish uranium production data, the paper relies on estimates of Pakistan's domestic uranium production reported in the biennial worldwide assessment of uranium resources and production, *Uranium Resources, Production and Demand,* published by the Organisation for Economic Co-operation and Development

(OECD) and the International Atomic Energy Agency (IAEA), commonly known as the "Red Book."[1] This article evaluates possible scenarios for the consumption of this uranium in the enrichment program, whose capacity may have varied over the years, and as fuel for the growing number of production reactors. Taken together, it is possible to construct a coherent picture of the program as a whole.

The next section of the paper describes the availability of uranium for Pakistan's nuclear program from both domestic sources and imports over the years. The following sections review the consumption paths of this uranium, presenting possible scenarios for the evolution of Pakistan's enrichment capacity, the associated uranium requirements and the current and future uranium needs for the Khushab production reactors.

In the final section, the preceding analysis of possible uranium flows is used to construct an integrated picture of Pakistan's military program, linking its uranium enrichment and plutonium production capacities. It also presents an updated estimate of Pakistan's stock of fissile material for weapons and projections of how these stocks may grow in the future.

There are important uncertainties regarding what the status of Pakistan's fissile material production program could be even a decade from now. It is unclear, for instance, if the severe earthquake of October 2005 damaged Pakistan's centrifuges at Kahuta (it is assumed here that the damage, if any, was repaired without affecting production) and whether a future earthquake may cause more serious problems and may require the replacement of many centrifuges.

Pakistan also may decide that it has produced sufficient fissile material to meet military requirements: the United States, Russia, United Kingdom, France and China have already ended their production, India, Israel and North Korea have not.[2] It is also possible that faced with worsening political instability and violence, Pakistan may choose to end fissile material production as a security measure. More likely perhaps is the successful negotiation of the long awaited Fissile Material Cutoff Treaty, which would ban the production of fissile material for weapons. Pakistan, despite its current concerns about the scope of such a treaty, might not be able to resist international pressure to end its production of fissile material for weapons even if it chose not to sign the treaty.[3] Neither Pakistan nor India has conducted nuclear tests since 1998 even though they are not signatories to the Comprehensive Test Ban Treaty.

There are also technical and economic issues of maintaining and replacing aging infrastructure, and the development of new capacity. By 2020, Pakistan's original centrifuges would be over 40 years old, and any new capacity installed soon after the 1998 nuclear tests as well as the Khushab-I reactor would be over 20 years old. It is also unclear what Pakistan's uranium resources and mining capacity might be 10 or 20 years from now because the OECD/IAEA "Red Book" only projects uranium production and demand to 2030. For these reasons, the present analysis limits projections of Pakistan's fissile material production to 2020.[4]

URANIUM PRODUCTION IN PAKISTAN

In 1957, the Pakistan Atomic Energy Commission (PAEC) launched a search for domestic deposits of uranium.[5] Uranium was discovered in May 1959 by the Geological Survey of Pakistan at Bagalchore (Bagalchur), near Dera Ghazi Khan, in the southern part of the province of Punjab.[6] The ore grade at Bagalchore was initially described as ranging from 0.05–0.5 percent, with an average of approximately 0.15 percent uranium.[7] Later reports indicate the typical grade as ranging from 0.03–0.1 percent and distributed in the form of lenses up to several tens of meters long and less than a few meters thick, reaching depths of over 150 meters.[8] A 1980 assessment reported reserves, as of 1976, as 150,000 tons at a cut-off grade of 0.1 percent U_3O_8, containing 181 tons of uranium, with "no past production."[9]

According to PAEC, the mine and co-located uranium mill opened in 1977–78.[10] However, large scale mining at Bagalchore appears to have started after 1980, with reports that purchases of equipment including "loaders, cranes and mining machines" were made between 1980 and 1985.[11]

The IAEA Nuclear Fuel Cycle Information System (iNFCIS) database reports the mill started up in 1978.[12] This may have marked the start of an initial period of pilot scale activity, described in Pakistani reports as "small scale mining and processing activity on experimental basis," with "a chemical processing mini-plant of half a ton ore per day capacity ... functioning satisfactorily."[13] This equates to a production rate of less than 200 kg a year for ore containing 0.1 percent uranium. The mill's design capacity is reported variously as 300 tons of ore per day,[14] and 30 tons of uranium per year.[15] If both reports are correct, this suggests an average ore quality of 0.03 percent.

The Bagalchore mine was reported to be nearly exhausted by 1998.[16] It was reportedly closed by 2000 and the site used to dump radioactive waste.[17] The IAEA's World Distribution of Uranium Deposits database reports the original amount in the Bagalchore deposit as less than 500 tons and the deposit as now being depleted.[18]

A second uranium mine was opened at Qabul Khel in 1992, and mining of deposits at the Nanganai and Taunsa deposits (both located near Dera Ghazi Khan) started in 1996 and 2002 respectively, all using in situ leaching technology.[19] This extraction method is typically used for low-grade ores. The IAEA's World Distribution of Uranium Deposits database (UDEPO) reports an initial resource of 500–1000 tons of uranium at the Qabul Khel site.[20]

Table 1: Estimated annual domestic uranium production for Pakistan.

Year	Uranium production (tons)	Cumulative production since 1980 (tons)
1980	23	23
1981	23	46
1982	23	69
1983	23	92
1984	23	115
1985	23	138
1986	23	161
1987	23	184
1988	23	207
1989	23	230
1990	30	260
1991	30	290
1992	23	313
1993	23	336
1994	23	359
1995	23	382
1996	23	405
1997	23	428
1998	23	451
1999	23	474
2000	23	497
2001	16	513
2002	38	551
2003	40	591
2004	40	631
2005	40	671

Source: OECD/IAEA, *Uranium Resources, Production, and Demand*, 1990, 1997, 1999, 2005, and 2007.

The OECD/IAEA "Red Books" provide estimates for uranium production in Pakistan from 1980 onwards and are summarized in Table 1.[21] The data shows a roughly constant annual rate of approximately 23 tons of uranium, until about 2000 (when the Bagalchore mine closed) and a higher rate of approximately 40 tons per year from 2003 onwards. This increase in production is presumably due to the new mine at Qabul Khel.

Pakistan continues to search for new uranium sources at great expense.[22] However, no significant new finds or new mines have been reported as of 2009.

Uranium Imports

Pakistan appears to have imported some uranium. It signed a safeguards agreement with the IAEA in 1977 for the import of uranium concentrate from Niger.[23] It is reported to have bought at least 60–110 tons of uranium directly from Niger.[24] There also have been reports that Libya may have purchased uranium from Niger starting in 1978 and then secretly sold or transferred some of it to Pakistan.[25] But as part of the IAEA's verification activities in Libya since 2003 it has been reported that Libya imported a total of 2263 tons of uranium yellowcake between 1978 and 1981, containing 1587 tons of uranium, and that all of this has been accounted for in Libya's inventory.[26] This implies Pakistan may only have imported up to 110 tons of uranium and these imports were under IAEA safeguards. Pakistan also apparently received 15 tons of uranium hexafluoride and 50 kg of HEU from China in 1982.[27] This is not included in the accounting presented here.

CONSUMPTION OF URANIUM IN REACTORS

Pakistan has two operating power reactors, KANUPP and Chashma, and a third under construction. In addition, it has a dedicated reactor in Khushab that produces plutonium for weapons, and two similar reactors under construction.

KANUPP and Chashma are under safeguards. The 300 MWe Chashma reactor is fueled by low enriched uranium (LEU) supplied by China, and is not considered further in this analysis. KANUPP, a 125 MWe heavy water reactor fueled with natural uranium, was purchased from Canada and began operating in 1970. It was initially fueled by Canada. Following the 1974 Indian nuclear test and Pakistan's refusal to sign the Non-Proliferation Treaty (NPT), Canada ended its fuel supply. In response, Pakistan developed its own fuel fabrication capability, producing its first test fuel bundle in 1978.[28]

The total uranium consumption for KANUPP from 1980 to 2009 can be derived from its declared electricity production in this period, and amounts to 150 tons (assuming a fuel burn-up of 7400 MWd/t).[29] Since this reactor is safeguarded, we assume the uranium feed was largely taken from safeguarded imported material rather than unsafeguarded domestic production. This latter stock is assumed to have been dedicated to the military program.

Pakistan's third operating reactor, the Khushab plutonium production reactor cannot use safeguarded imported uranium and relies exclusively on domestic natural uranium. It is reported to be a heavy water natural uranium reactor with a capacity of approximately 50 MWt.[30] This seems a reasonable estimate of the capacity, given that images of this reactor show its dome to be very similar in size to the dome of India's 40 MWt CIRUS reactor (see Figure 1). Work on Khushab started in 1986–87 and the reactor came on line in 1998.[31] This would have required its fuel to have been fabricated starting about 1997 if not before. The irradiation time for the fuel would have been short, to allow for the low-burn (typically 1000 MWd/t) required to produce weapon grade plutonium. The first batch of spent fuel could have been taken out in 1999, cooled and reprocessed in 2000. On 16 March 2000, CBS News

Figure 1: Khushab I reactor–the reactor building is at the center and the eight cooling towers are at the right (IKONOS satellite imagery courtesy of GeoEye).

reported that the U.S. had acquired air samples in Pakistan showing traces of krypton-85, indicative of active reprocessing.[32]

Two more reactors are being built in Khushab (see Figure 2).[33] The two new reactor buildings appear to be identical to each other but different from Khushab I. The construction of Khushab II appears from satellite imagery to have started in 2001–2002, while work on Khushab III started in 2005 or 2006.[34] Images from September 2008 have been interpreted as suggesting that the Khushab II reactor may be completed late in 2009.[35]

An initial estimate of the capacity of these reactors claimed a power of at least 1000 MWt.[36] However, a Pakistani official indicated Khushab II could be much smaller than 1000 MWt, while a U.S. official said “the reactor will be over 10 times less capable.”[37] Subsequent estimates are that the reactor may be much closer to Khushab I in size, with a capacity of 40–100 MWt.[38] U.S. government sources go further in suggesting that “intelligence indicated that the emerging reactor appeared to be roughly the same size as the small one Pakistan currently uses to make plutonium for its nuclear program.”[39]

The cooling towers offer one indication of the power of these reactors. Inspection of the images of Khushab I and Khushab II show both to have an

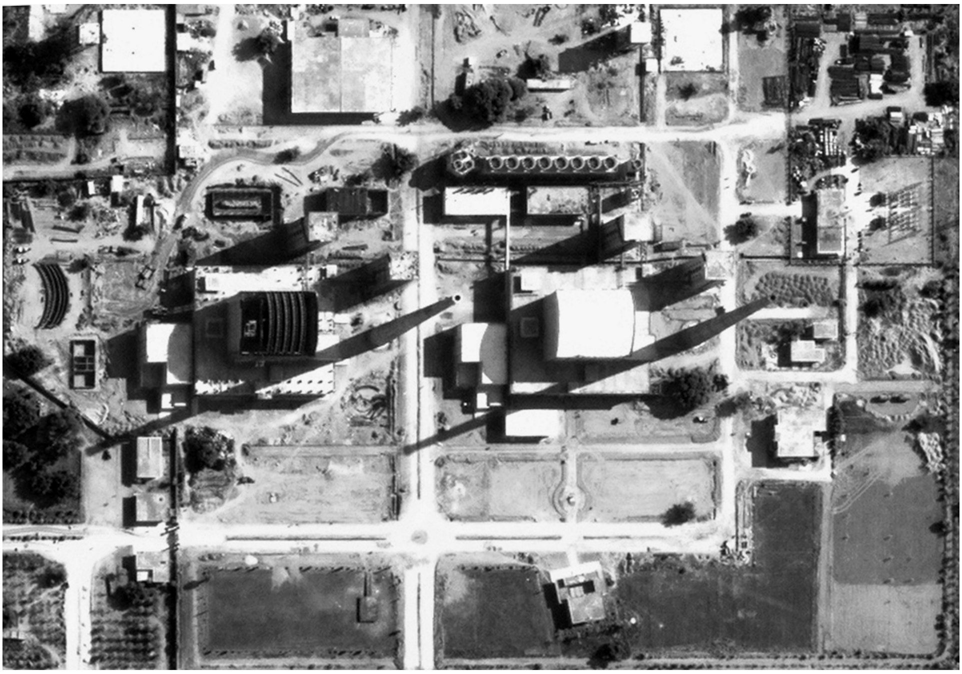

Figure 2: Khushab III (left) and Khushab II (right) under construction, as of January 2009 (Digital Globe imagery, courtesy of ISIS).

identical array of eight mechanical-draft cooling towers of approximately 5 m diameter each. Khushab II seems to have a few more cooling towers of a different design. It is not clear if these are part of the cooling mechanism for the reactor or serve some other purpose. In any event, these additional towers seem to add at most approximately 20 percent to the area of the main cooling rack of eight towers.

Furthermore, Pakistan's estimated current domestic uranium production of 40 tons/year can only support approximately 150 MWt of total capacity operating at 70 percent efficiency with the low-burn associated with weapons plutonium production reactors.[40] If Pakistan operates all three Khushab reactors, it appears unlikely that the current uranium production rate would allow Khushab II and Khushab III to have a capacity very different from 50 MWt. Therefore, for the purpose of this analysis, all three Khushab reactors are taken to be 50 MWt each.

To provide fuel for the new reactors, Pakistan may have had to expand its uranium processing and fuel fabrication capacity. Satellite imagery appears to show an expansion of the Chemical Plants Complex at Dera Ghazi Khan, which reportedly produces both uranium oxide for reactor fuel fabrication and uranium hexafluoride for enrichment.[41] It is assumed here that fuel fabrication for the reactors would start from 2008 and 2009 and the reactors would begin normal operation in 2009 and 2010 respectively.

Pakistan also may have had to expand its reprocessing capacity to deal with the spent fuel from the new reactors, which together with Khushab I would produce a total of 39 tons of heavy metal a year. It is believed that Pakistan reprocesses spent fuel from Khushab I at its New Labs facility near Rawalpindi. Imagery from 2009 suggests that Pakistan may have built a second reprocessing plant at the New Labs to handle the additional spent fuel (see Figure 3).[42] There are also indications that between 2002 and 2006 Pakistan may have resumed work on a large reprocessing plant at Chashma.[43] This facility was to have been built by France in the mid 1970s to handle 100 tons of spent fuel per year, but the deal was cancelled at an early stage of construction.

PLUTONIUM PRODUCTION

In a heavy water reactor, at a burn-up of 1000 MWd/t, typical for producing weapons grade plutonium, the spent fuel contains approximately 0.9 kg of plutonium per ton of spent fuel.[44] A reactor of 50 MWt, operating at 70 percent capacity, at this burn-up will consume approximately 13 tons of natural uranium as fuel per year, and produce approximately 11.5 kg of weapon grade plutonium per year.

The timeline for the Khushab production reactors suggests that Pakistan has been accumulating weapon grade plutonium since 2000 from Khushab I. By 2010, Pakistan could have accumulated approximately 115 kg, equivalent to just over 20 simple fission weapons, assuming 5 kg per weapon. The plutonium from the new Khushab reactors could become available in 2011 and 2012 respectively. The cumulative plutonium produced in the Khushab reactors' spent fuel up to 2020 is shown in Figure 4. This suggests that by 2020, Pakistan could have produced a total of approximately 450 kg of plutonium.

REPROCESSED URANIUM

Reprocessing spent fuel to recover plutonium also creates a stream of uranium containing a large fraction of the initial uranium-235 that can be used as feedstock for enrichment. However, such use is complicated because of contamination by other uranium and transuranic isotopes and chemical impurities.

It is possible to estimate to first order the uranium isotopic composition or vector in the spent fuel of a natural uranium fueled production reactor. Each ton of natural uranium contains 992.89 kg of uranium-238 and 7.11 kg of uranium-235. The annual energy release from a 50 MWt production reactor working at 1000 MWd/t at 70 percent capacity comes from 306×10^{23} fissions, i.e., the fission of approximately 12 kg of uranium-235.[45] The reactor consumes as a whole 12.8 tons of fuel per year and 0.937 kg of uranium-235 is consumed per ton of fuel. Thus, the annual discharge of spent fuel of a Khushab

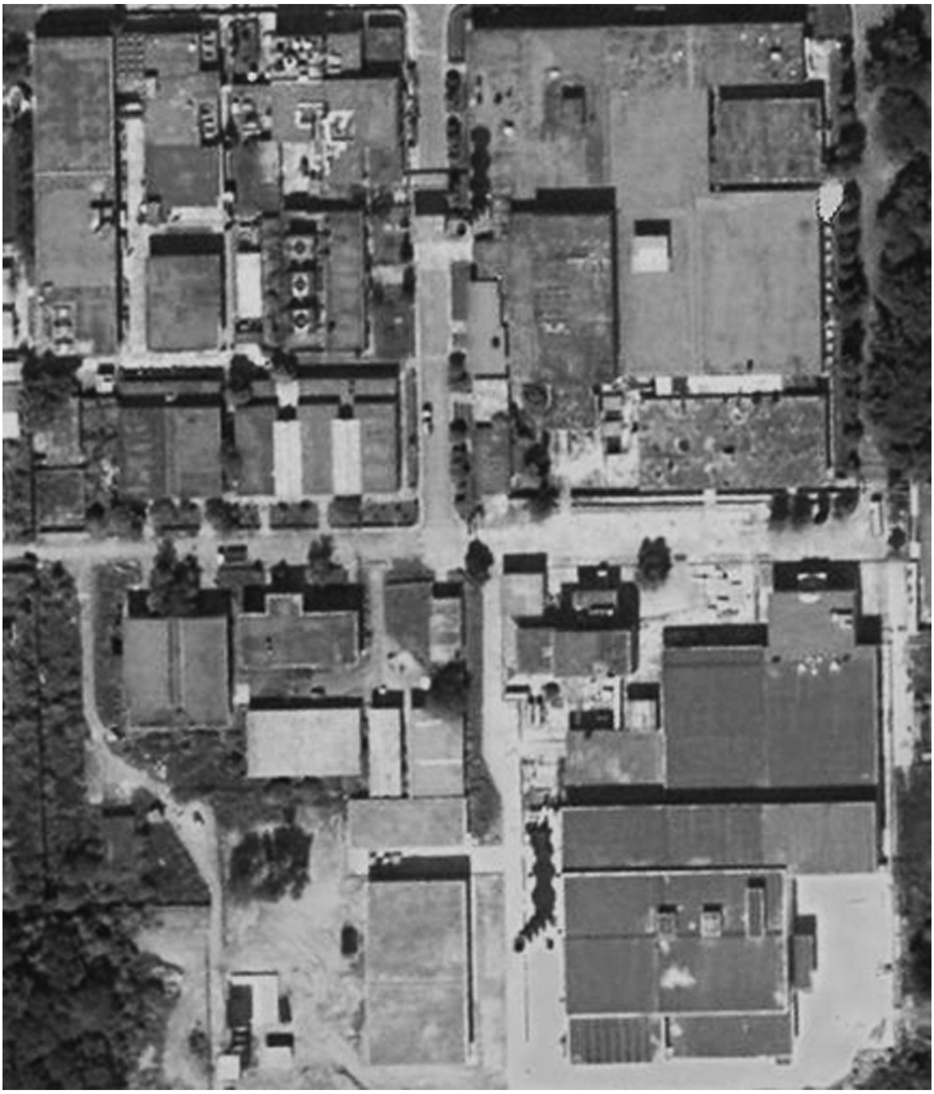

Figure 3: Original reprocessing plant (top right) and possible new reprocessing plant (bottom right) at the New Labs site, Rawalpindi, September 2006 (Google Earth imagery, courtesy of ISIS).

reactor would contain approximately 12.8 tons of uranium, with 0.62 percent uranium-235.

Reprocessed uranium also contains the isotopes uranium-232, uranium-233, uranium-236 and uranium-237 that are not present in natural uranium. The abundances of these isotopes in reprocessed uranium depends on the type of fuel, the initial uranium-235 enrichment, the burn-up of the fuel, and the cooling time of the spent fuel prior to reprocessing. Since enrichment serves

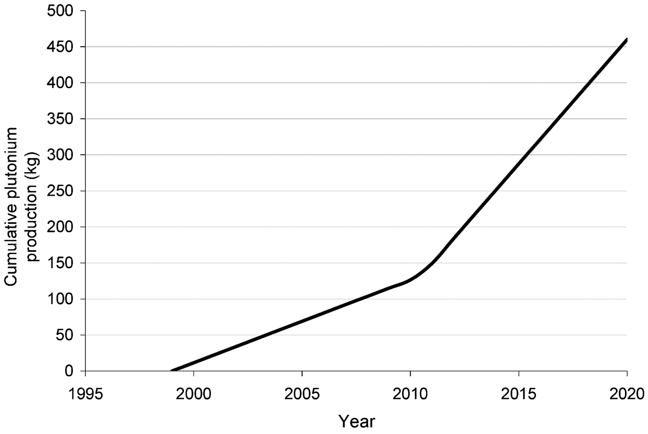

Figure 4: Cumulative plutonium production from the Khushab reactors to 2020.

to increase the relative abundance of lighter isotopes, the radioactivity of enriched reprocessed uranium is greater than that of enriched natural uranium. The isotope uranium-232 (69 year half-life) is a problem because it has a decay chain that includes daughter products that are significant beta and gamma emitters (lead-212, bismuth-212, and titanium-208). The other isotopes are less significant as radiological hazards. Table 2 lists the uranium isotopic abundances expected in low burn-up heavy water reactor fuel.[46]

There are also transuranic isotopes and chemical impurities in reprocessed uranium that follow the uranium through the fluorination and enrichment process, the abundance of which depends on the efficiency of reprocessing operations.[47] As result, the production and use of enriched reprocessed uranium usually requires dedicated processing facilities with additional shielding to protect operators, and may require modified operating procedures at the enrichment facility including reducing the time between UF_6 conversion and enrichment, purifying of the UF_6, special filters, and special handling of feed and product cylinders.[48]

Table 2: Uranium isotope abundances in 1000 MWd/t PHWR spent fuel.

Isotope	Abundance (wt%)
U-232	1.013×10^{-10}
U-233	2.550×10^{-9}
U-234	0.005
U-235	0.616
U-236	0.015
U-238	99.37

Even though it is more difficult and costly, reprocessed uranium has been enriched by various countries.[49] The United Kingdom, for instance, enriched reprocessed uranium (containing 0.4 percent uranium-235) from its natural uranium fueled Magnox reactors at Capenhurst gaseous diffusion plant (to 0.7 percent) and then further enriched it (to 2.6–3.4 percent) at Urenco's Capenhurst centrifuge plants for fuel in advanced gas-cooled power reactors.[50] Both the United States and Russia enriched reprocessed uranium recovered from plutonium production reactors to 90 percent uranium-235, i.e., to the level typical for weapons.[51] This may be an option for Pakistan as well if it faces a natural uranium shortage for its enrichment program. The 15 tons of uranium hexafluoride that Pakistan possibly received from China in 1982 may have contained reprocessed uranium.

URANIUM ENRICHMENT

The history of Pakistan's uranium enrichment centrifuge program is marked by considerable secrecy, speculation and some drama. In order to make a coherent estimate of HEU production and uranium consumption it was necessary to cull out of various reports a possible scenario of how many centrifuges, and of what capacity, were successfully operating at different periods. This exercise draws heavily on the sources cited by Albright, Berkhout, and Walker.[52]

PIECING TOGETHER PAKISTAN'S CENTRIFUGE STORY

Pakistan initially explored a number of techniques for uranium enrichment, including laser, centrifuge and diffusion.[53] A decision was made to proceed with a gas centrifuge enrichment plant in November 1974.[54] Pakistan also contracted with a German company to build a uranium hexafluoride plant, with a reported capacity of approximately 200 tons per year, which apparently began work in 1980.[55]

The centrifuge program began at the newly built Energy Research Laboratory at Kahuta with two types of designs. Pakistan started out with the Dutch CNOR-SNOR based centrifuge (sometimes referred to as P-1 in the Pakistani context) and achieved separation of uranium in its prototype centrifuge in June 1978 and the first cascade of 54 machines was set up by early 1979.[56] Reports quoting A.Q. Khan indicate that Pakistan was first able to enrich natural uranium up to a few percent uranium-235 by 1980,[57] and up to weapon grade by 1982.[58] However, these were presumably small scale samples. A 1983 U.S. State department briefing paper noted that Pakistan had "not yet produced significant quantities of enriched uranium."[59]

Large scale enrichment using cascades of P-1 centrifuges apparently proved problematic for Pakistan. Their experience with the German design

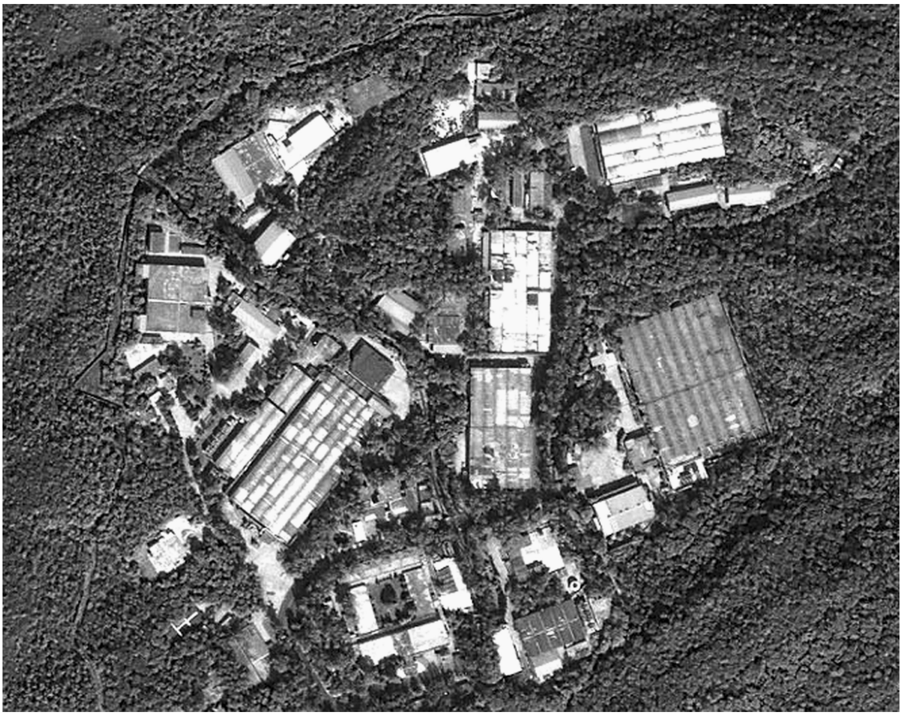

Figure 5: Northern (original) production area of the Kahuta enrichment plant (IKONOS satellite imagery courtesy of GeoEye).

G-2 machines (termed P-2 in the Pakistani context) appears to have been better and they were in mass production by the mid 1980s.[60] A 1986 report claims that at Kahuta the two types of centrifuges were housed in "two big halls set slightly at an angle to each other . . . contain[ing] about 7000 centrifuges"[61] (see Figure 5). However, only a thousand or so machines were believed to be operational in 1986.[62] At some stage, probably in the mid 1980s, Pakistan limited its use of P-1 machines, and moved to using P-2 and later possibly more advanced machines.[63]

A.Q. Khan subsequently claimed that by 1984 Pakistan had produced enough uranium for a nuclear test, which they were hoping to conduct by 1986.[64] An internal U.S. memo to Henry Kissinger in 1986 claimed that Kahuta had a nominal capability to produce "enough weapons grade material to build several nuclear devices per year."[65] By 1988, it was reported that Pakistan had enough weapon grade uranium for four to six weapons (i.e., 100–150 kg of HEU).[66] A U.S. official claimed in late 1991 that Pakistan had sufficient HEU for as many as six weapons.[67]

There is little information about the possible cascade design used by Pakistan. One source is the indictment submitted in a South African court concerning a project located there to manufacture an enrichment plant for export to Libya using a Pakistani design provided by the A.Q. Khan network.[68] The cascade design plans were described as “the product of original German drawings and descriptions as adapted by Pakistan test results, experience and reference calculations” and show four blocks of cascades totaling 5832 centrifuges. The first block contained two parallel cascades of 1968 machines each and enriched natural uranium to 3.5 percent uranium-235. The second block had 1312 machines and enriched this 3.5 percent material to 20 percent uranium-235. The third block, with 456 machines, further enriched this material to 60 percent uranium-235. The final block, of 128 machines, produced 90 percent enriched material. There are separate feed and withdrawal stages for each of these five cascades. This would allow, in principle, each of these enrichment stages to be carried out in separate facilities.

The South African report would imply Pakistan might have had a cascade design of approximately 6000 machines. Note, however, that one can successfully run such a cascade with half this number of centrifuges, i.e., 3000 machines, provided the number of machines at each stage were also cut in half, while retaining the same stage-to-stage ratios. This is consistent with reports that the plans for Kahuta in the late 1980s called for 2000–3000 centrifuges and a claim by a U.S. official that by 1991 Kahuta had approximately 3000 machines operating.[69] If these 3000 machines were P-1 or P-2 centrifuges, respectively with 3 and 5 kgSWU/year (or SWU) each, this would give a total capacity of 9000 or 15,000 SWU for the full cascade depending on the machine.

Taking these reports into account, a plausible scenario for the first phase of Pakistan’s enrichment program (until about 1990) may be as follows:

1. Pakistan had no substantial enrichment capacity until approximately 1982;
2. It achieved sufficient capacity to make 20 kg/yr of HEU during 1983–1985. (This calls for a separative power of approximately 3000 SWU, produced by approximately 1000 centrifuges of 3 SWU each), and
3. It increased the capacity linearly to 9000–15,000 SWU by 1990, through a mix of P-1 and the more powerful and less problematic P-2 machines.

A new period in Pakistan’s enrichment began in 1990–1991. The U.S. had unsuccessfully sought to end Pakistan’s enrichment program from its inception; the 1972 Symington Amendment and 1985 Pressler Amendment banned aid to Pakistan because of its enrichment activities.[70] However, these restrictions were waived by successive U.S. administrations for geo-strategic reasons, and thus enrichment continued. During this time, Pakistan committed to enrich uranium only to 5 percent, but according to U.S. officials appears to have enriched far above this level.[71] There was, however, a brief interruption in HEU production starting in mid-1989 in anticipation of Prime Minister

Benazir Bhutto's visit to the U.S., but production was resumed by the spring of 1990.[72] The U.S. finally imposed sanctions in 1990, and in an attempt to have sanctions lifted, Pakistan adopted an indefinite moratorium on HEU production in 1991.[73] Pakistan's Chief of Army Staff at the time, Mirza Aslam Beg, seems to have confirmed such a moratorium and explained that Pakistan began to produce only LEU, possibly up to 5 percent uranium-235.[74]

U.S. officials claim intelligence confirming that Pakistan stopped production of HEU at least until the 1998 nuclear tests, even though after the tests A.Q. Khan denied this.[75] Note, however, that the cumulative production of HEU in the two cases would eventually become equal, as long as the enrichment plant was operated at its full capacity during this period. This is because the total amount of HEU produced with a given enrichment (and tails) depends only on the utilized SWU capacity and not on whether the enrichment was done in stages. (See the formula for SWU capacity below.) In this study, it is assumed that HEU production was stopped.

If, as Pakistan's Chief of Army Staff claimed, HEU production had been suspended, the 1998 tests presumably ended the need to exercise such restraint. It is assumed here that enrichment to 90 percent resumed in mid-1998, soon after the tests. HEU production could have been resumed quickly by using as feedstock the LEU that had been accumulated in the years since 1991. Once this stock was exhausted, Pakistan could have returned to using natural uranium feed.

Meanwhile construction of additional enrichment capacity seems to have continued. Satellite imagery suggests a second production area was added at some stage to the Kahuta facility (see Figure 6).[76] Pakistan developed the indigenous capability to produce maraging steel and some other components for centrifuges. It also imported components, including a 1995 purchase from China of 5000 ring magnets, which serve as part of the upper bearings of centrifuges, and would allow for the construction of perhaps several thousand additional machines.[77]

There are also reports that in the 1980s, Pakistan started developing more powerful P-3 and P-4 centrifuges, resembling Urenco's 12 SWU 4-M and 20 SWU TC-10 machines respectively.[78] There is no clear information as to whether, when and how many of these more advanced centrifuges may have been put into operation by Pakistan. It is assumed here that any increase in capacity, whether by additional P-2, P-3 or P-4 machines, was brought into operation in 1999, soon after the nuclear tests.

The characteristics of the various generations of Pakistani centrifuges as inferred from various published reports are summarized in Table 3.

It has been assumed in this paper that Pakistan's enrichment capacity grew from 3000 SWU in 1983 to 15,000 SWU in 1990. For the period after 1990, this study considers four enrichment scenarios built from modules consisting of 3000 centrifuges, derived from the Pakistani cascade drawings supplied to a South African manufacturer. These scenarios are:

Figure 6: Southern production area of the Kahuta enrichment plant (IKONOS satellite imagery courtesy of GeoEye).

1. A continuing enrichment capacity of 15,000 SWU, as some analysts seem to assume;[79]
2. An increase in enrichment capacity from 15,000 to 30,000 SWU starting from 1999, possibly from 6000 P-2 machines;

Table 3: Characteristics of Pakistani centrifuges.

Centrifuge	Rotor material	Number of segments	Total length (m)	Separative power kg SWU/year	Peripheral velocity (m/s)
P-1[1]	Aluminum	4	2	1–3	350
P-2[2]	Maraging steel	2	1	∼5	450
P-3[3]	Maraging steel	4	2	∼12	485
P-4[4]	Maraging steel	6	∼3	∼20	508

[1] Mark Hibbs, "Classified Dutch Report Suggested Khan Saw Key 4-M Centrifuge Data," *Nuclear Fuels*, 17 January 2005.

[2] Mark Hibbs, "Report Suggests Pakistan Bought Components For Two Steel Centrifuges," *Nuclear Fuels*, 4 July 2005.

[3] Mark Hibbs, "Pakistan Developed More Powerful Centrifuges," *Nuclear Fuels*, 29 January 2007.

[4] Mark Hibbs, "P-4 Centrifuge Raised Intelligence Concerns About Post-1975 Data Theft," *Nucleonics Week*, 15 February 2007.

3. An increase in enrichment capacity from 15,000 to 45,000 SWU starting from 1999, coming possibly from cascades of 3000 P-2 machines and 3000 P-3 machines; or
4. An increase in enrichment capacity from 15,000 to 75,000 SWU starting from 1999, coming possibly from cascades of 3000 P-2 machines and 3000 P-4 machines.

In these scenarios, the total enrichment capacity need not be at Kahuta alone. It could be distributed across additional sites. There have been claims that Pakistan may have enrichment facilities at Sihala, Golra and Gadwal.[80] Gadwal was described recently as a facility where enriched uranium is enriched further to weapons grade.[81] For the purposes of the analysis below, however, only the total SWU capacity is relevant.

The maximum capacity considered here is 75,000 SWU. Since it will be safeguarded, the proposed 600,000 SWU enrichment plant at Chak Jhumra, near Faisalabad, in Punjab province, is not included.[82] This capacity is intended to fuel an ambitious expansion of Pakistan's nuclear power program, with a target of 8800 MW by 2030.[83] It is unlikely that these plans will be realized since Pakistan is currently banned from purchasing reactors by the rules of the Nuclear Suppliers Group.[84] If reactors sales were to be permitted, it is likely that providers would supply both reactors and fuel under safeguards—as was the case with the two Chashma power reactors supplied by China to Pakistan.

The analysis that follows will assess the viability of the four enrichment scenarios using the constraint of uranium supply discussed above.

URANIUM CONSUMPTION AND HEU PRODUCTION

In this section, the uranium consumption and HEU production are estimated for the four scenarios outlined above.

The basic equations linking uranium feed (F), product (P) and tails (T) and the respective concentrations (n) to SWU capacity are well known.[85] These are

$$\frac{n_p - n_t}{n_f - n_t} = \frac{F}{P} = \frac{T}{P} + 1$$

$$\text{SWU capacity} = P \cdot V(n_p) + T \cdot V(n_t) - F \cdot V(n_f)$$

Where $V(x) = (2x - 1)\ln(\frac{x}{1-x})$ is the "value function."

Thus P, the amount of HEU produced, and the corresponding feed F can both be determined from the SWU capacity for a given set of concentration fractions.

Table 4: SWU per kg of Product for Various Feed, Product and Tails Concentrations.

Concentration of U-235 in feed n_f	Concentration of U-235 in product n_p	Concentration of U-235 in tails n_t	Ratio of feed to product F/P	Separative work per kg of product SWU/*P*
0.71%	90%	0.3%	218	193
0.71%	5%	0.3%	11.4	7.2
0.71%	90%	0.5%	424	154
0.71%	5%	0.5%	21	5.3
0.71%	90%	0.1%	147	293
5%	90%	0.3%	19	56
5%	90%	0.5%	20	48
5%	90%	0.1%	18.4	73
0.62%	90%	0.3%	280	208
0.62%	90%	0.1%	173	320
0.3%	90%	0.1%	450	500

For convenience, Table 4 gives the values of SWU per kg of product for some useful combinations of feed, product and tails fractions.

Using these equations one can calculate that the enrichment capacities of 15,000, 30,000, 45,000 and 75,000 SWU, all producing 90 percent HEU from natural uranium and with 0.3 percent tails, will require annual natural uranium feeds respectively of 17 tons, 34 tons, 51 tons and 85 tons. In addition, the Khushab reactors will each consume approximately 13 tons a year. Meanwhile, as previously noted, it is assumed that the domestic natural uranium production in Pakistan has been constant at 40 tons for a number of years. Thus, eventually the annual production of natural uranium will not be able to meet annual requirements. Pakistan would then have to dip into the reserve unsafeguarded stocks accumulated from the early years when the annual requirement was less, but these too would run out after some time. Clearly, the higher the SWU capacity of the centrifuge plant, the sooner this will happen.

Although the natural uranium supply will be depleted, there are two other sources of feed material for centrifuges, namely the depleted uranium tails from previous enrichment activity and the uranium recovered from reprocessing spent fuel. Enrichment of each ton of depleted uranium (with 0.3 percent uranium-235) would yield 2.2 kg of 90 percent HEU if stripped further down to produce tails containing 0.1 percent uranium-235.[86] It would also be possible to use recovered uranium from reprocessed Khushab spent fuel, which may contain approximately 0.62 percent uranium-235, as noted above. Both these options are included in the following calculations.

In all cases, it is assumed the depleted uranium tails are used as feed for enrichment after the natural uranium reserve is exhausted. Note however that Pakistan is reported to use depleted uranium to manufacture armor piercing ammunition.[87] This use is assumed to be small and may, in any case, involve the depleted uranium tails generated by the second enrichment process. When the stock of depleted uranium tails is exhausted, the enrichment facility is assumed to be fed with reprocessed uranium. This is because the latter contains traces of other isotopes, which would contaminate the centrifuges.

Figure 7a–d shows the annual HEU production from 1980 to 2020 for the four enrichment capacities considered here. These figures contain several interesting features. First, note that the following five features are common to all four cases:

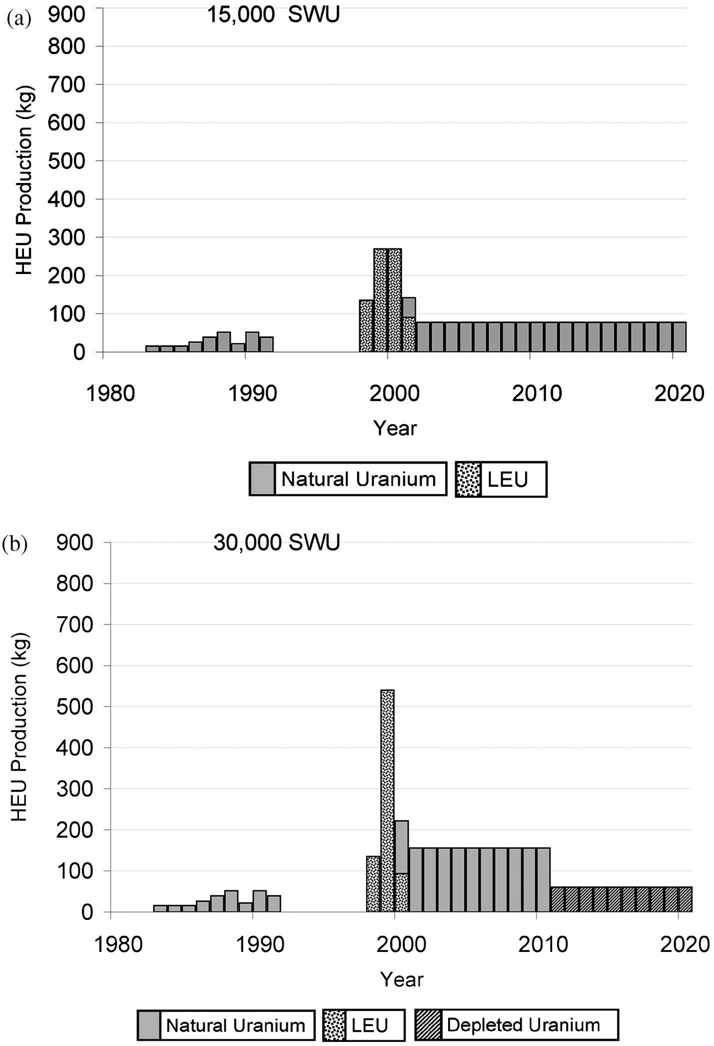

Figure 7: (a-d) Annual HEU production for enrichment capacities of 15,000 to 75,000 SWU. Regions with different shadings correspond to different feed material. Light grey represents natural uranium, dotted areas represents LEU, and hatched areas represent depleted uranium tails, and the cross-hatched areas, in (c) and (d), correspond to reprocessed uranium.

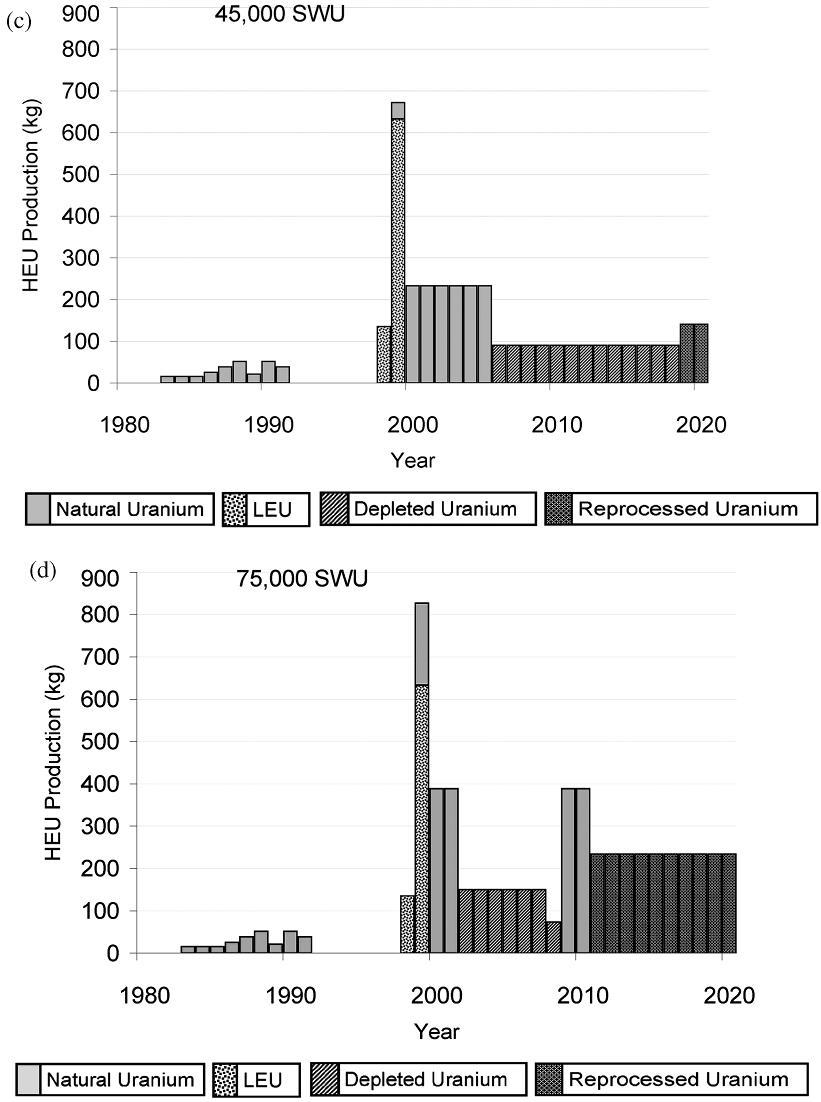

Figure 7: *(Continued)*

1. HEU production is common until 1998 because the enrichment capacity up to that time is the same in all the cases. The gradual increase during this period corresponds to a constant capacity of 3000 SWU from 1983 to 1985 which then linearly increases to reach 15,000 SWU in 1990;
2. There is a small dip in HEU production in 1989–1990 due to the brief moratorium associated with the visit by Benazir Bhutto to the United States;

3. After 1991, HEU production stops until 1998. This was the period of the HEU moratorium. During this time, however, the enrichment program produced LEU (assumed to have been 5 percent uranium-235). It is estimated that nearly 15 tons of LEU was accumulated in this period;
4. There is a sharp increase in HEU production from 1998 to about 2000 due to the use of the accumulated LEU as feed material. The time taken to enrich this LEU to HEU decreases with increasing SWU capacity. This is reflected in the increasing height of the bar from Figure 7(a) to Figure 7(d). The total amount of HEU produced in this fashion is approximately 750 kg for all four cases; and
5. All the LEU has been converted to HEU by 2001. After this, use of natural uranium as feed is resumed until it is exhausted.

Note that in the case of 15,000 SWU case, Figure 7(a), natural uranium lasts beyond 2020. After about 2001 when the LEU stock has all been enriched, the centrifuges revert to using natural uranium at a steady rate of 17 tons to produce almost 80 kg of HEU per year. This would be drawn from the available 200 ton stockpile of natural uranium while it lasts (roughly until 2024), while the 40 tons of annual production could fuel the Khushab reactors. There is no need to resort to either depleted uranium or reprocessed uranium as feed.

In the 30,000 SWU case, Figure 7(b), natural uranium stock will be exhausted by 2011. The continuing annual production of 40 tons will be used up by the three Khushab reactors. After that, depleted uranium is used as feed for the centrifuges and is stripped down to 0.1 percent. HEU is produced during this period at a rate of 60 kg per year, consuming 27 tons of depleted uranium. This lasts beyond 2020 so that enriching reprocessed uranium stock is not needed.

For 45,000 SWU, Figure 7(c), natural uranium stock is exhausted by 2005, producing 233 kg of HEU per year.[88] Then the use of depleted uranium as feed begins, stripped down to 0.1 percent. This takes 41 tons of depleted uranium feed and produces 90 kg HEU annually. It is shown in the figure by the darker shade. By 2019, even the depleted uranium tails are exhausted.[89] From that point onwards, reprocessed uranium is used as feed (as shown by the cross-hatched area) to yield HEU at a rate of 141 kg per year with 0.1 percent tails.

For the 75,000 SWU case, Figure 7(d), the natural uranium reserves will be exhausted before about 2002.[90] Thereafter, accumulated depleted uranium is used as feed, which lasts until 2008, producing 150 kg of HEU per year. Concurrently, between 2002 and 2008, 184 tons of natural uranium are accumulated. This could be used for two years to produce 389 kg of HEU a year during 2009 and 2010. This is shown in Figure 7(d). After 2010, nearly all of the natural uranium is consumed in the three Khushab reactors, and the accumulated stock of tails has been exhausted. The enrichment plant will therefore

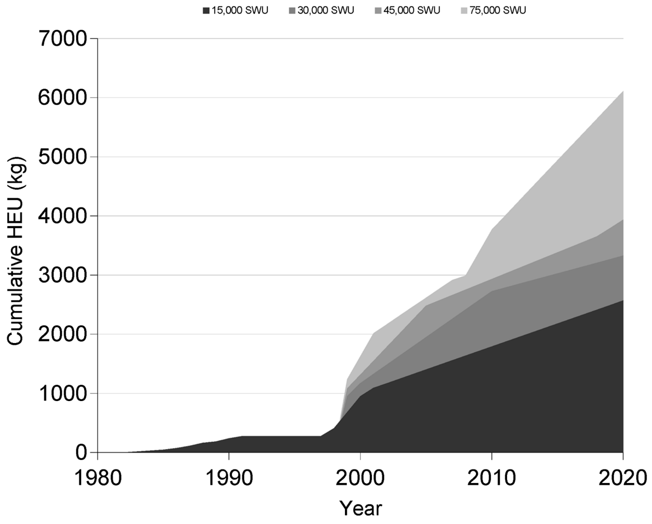

Figure 8: Annual growth of HEU stocks for four enrichment capacities, projected to 2020.

have to be fed by reprocessed uranium. A capacity of 75,000 SWU can take in a feed of 41 tons of reprocessed uranium to produce 234 kg of HEU per year (with 0.1 percent tails). Since the three Khushab reactors together produce 39 tons of reprocessed uranium per year, the additional two tons would have to come from accumulated stocks of reprocessed uranium. This will not be exhausted by 2020.

Figure 8 shows Pakistan's cumulative HEU stocks projected to 2020 for the four enrichment scenarios.

This assessment assumes a sequence of feedstock for the centrifuges; natural uranium feed, followed first by the use of LEU accumulated between 1992 and 1998, then by depleted uranium tails until they are exhausted, and finally by the use of reprocessed uranium. This sequence has been applied consistently for all four cases for simplicity and comparison. Different assumptions would produce different scenarios. For example, once the enrichment of the LEU stock to HEU is completed and the natural uranium feed falls below the annual requirement for enrichment, the remaining uranium stock could be mixed with the accumulated depleted uranium tails (0.3 percent uranium-235) to produce additional feed material, and this mixture stripped down to 0.1 percent tails. The mixing ratio in the feed material would be determined by the amount of natural uranium available and the enrichment capacity.

Pakistan may have skipped using depleted uranium and already started to use reprocessed uranium from the Khushab reactor as feed for its enrichment program. In 2004, while inspecting centrifuge components in Iran believed to have been imported from Pakistan, the IAEA reported that they had found "particles of LEU and HEU" that were attributed to "contamination originating from imported centrifuge components." The IAEA found that many of the samples had "an elevated uranium-236 content that suggests the use of recycled uranium as a feed material."[91] Traces of HEU were also found on centrifuge components that Pakistan sold to Libya, with the IAEA reporting "Environmental samples show low and high enriched uranium contamination on the floor of the L-1 centrifuge test area . . . on centrifuge and crashed rotor parts, on feed and take-off systems and on a mass spectrometer used in the tests. . . . Most of the U-236 content is similar to that found in the State that had supplied the L-1 centrifuge components."[92] This seems to indicate that Pakistan supplied both Iran and Libya centrifuge components previously used to enrich reprocessed uranium. This reprocessed uranium could, however, have come in the 15 tons of uranium hexafluoride that Pakistan possibly received from China in 1982 and enriched soon after, since some centrifuge component transfers to Iran and Libya took place before Khushhab spent fuel became available for reprocessing in 1999–2000.

CONCLUSION

The analysis presented here points towards a consistent picture of Pakistan's enrichment and plutonium production program based on a uranium balance assessment. It assumes Pakistan has relied solely on domestic uranium for both its uranium enrichment and its plutonium production programs, and utilizes the OECD/IAEA "Red Book" year by year estimates of Pakistan's domestic uranium production, which has varied between 20–40 tons per year for almost 3 decades. Pakistan has not been able to import uranium for many years because of international supply controls. Material that was imported earlier and was under IAEA safeguards cannot be used for weapons. This limited availability of natural uranium puts constraints on fissile material production for weapons.

Relying on public sources, there appear to be two different phases in Pakistan's fissile material production to date. The first phase was from the early 1980s to about 1998. During this period Pakistan's enrichment program grew from a modest 1000 centrifuges with a capacity of 3000 SWU to approximately 9000–15000 SWU. There was no production of weapons grade plutonium. During this phase, Pakistan would have had sufficient uranium to feed its centrifuges. In fact, in the initial stages there would have been a uranium surplus, leading to a small uranium reserve of nearly 200 tons by 1998.

In the next phase, the decade following the 1998 nuclear tests, approximately 1999–2009, the uranium demand may have increased for two reasons. Firstly, Pakistan began to produce weapons grade plutonium from its reactor at Khushab in 1999. It is estimated that for a reasonable capacity factor (of approximately 70 percent) Khushab requires approximately 13 tons of natural uranium fuel per year. Secondly, while some reports claimed that the enrichment capacity remained the same during this phase, others indicate that Pakistan may have commissioned additional P-2 centrifuges, and perhaps moved to more powerful P-3 and P-4 machines.

If the enrichment capacity had remained constant at 15,000 SWU during this second phase, then the requirement for enrichment (17 tons per year) and the Khushab reactor (13 tons per year) could have both been met from the annual production of 40 tons per year. For an enrichment capacity of 30,000 SWU, the uranium surplus reserves from the past would have to be tapped. If the capacity were much larger, such as 45,000 or 75,000 SWU, these reserves would be exhausted by approximately 2006 and 2002 respectively.

Once the natural uranium stocks are exhausted and the annual production rate is insufficient, as happens in the 45,000 and 75,000 SWU cases, Pakistan would have had either to mine more than 40 tons of uranium a year or find an alternative feed. One source of feed would be the depleted tails from previous enrichment activity. A second possibility would be to use reprocessed uranium recovered from the Khushab production reactors' spent fuel. Since these reactors are meant to operate at low burn-up to produce weapons grade plutonium, their spent fuel will still contain approximately 0.6 percent uranium-235, not much less than the 0.7 percent in natural uranium.

Since reprocessed uranium contains other more radioactive isotopes, making it more difficult to handle, it would be preferable to use it after the depleted tails from past enrichment activity are exhausted. The analysis presented here shows that supplies of uranium tails are sufficient to feed the centrifuges up until the present, for all the enrichment capacities up to 75,000 SWU.

Turning to the future, between now and 2020, the same general principles apply, but with the added difference that two more plutonium producing reactors are expected to be operating at Khushab. Assuming they are the same capacity as Khushab I (50 MWt) and operate at a 70 percent capacity factor, the three reactors combined will absorb almost the entire estimated current annual uranium production of 40 tons. Therefore to sustain its enrichment program, Pakistan will have to start using its stock of uranium, if any, from past surplus years, mine additional uranium, or use as feed its accumulated depleted tails or reprocessed uranium.

The periods for which natural uranium, the tails and reprocessed uranium will have to be used will of course depend on the enrichment capacity. The different cases are depicted in Figure 7, up to the year 2020, for the case of natural uranium production at 40 tons/yr. As shown there, the stock of natural uranium will be sufficient to feed a capacity of 15,000 SWU. For the 30,000 SWU case, augmenting natural uranium with accumulated depleted uranium tails can provide the additional feed. Use of reprocessed uranium will become necessary before 2020 for higher enrichment capacities. A capacity up to 75,000

SWU can be fully operated this way at least until 2020. Evidence of uranium-236 in LEU and HEU particles on Pakistan-supplied centrifuge components in Iran and Libya suggest Pakistan may have enriched some reprocessed uranium early in its program.

Depending on the enrichment capacity and, where required, by resorting to the use of depleted uranium and reprocessed uranium as feed, Pakistan could have accumulated by 2020, a stock of between 2500–6000 kg of 90 percent enriched HEU for weapons. If all three Khushab reactors have a capacity of 50 MWt, Pakistan could by 2020 also have accumulated approximately 450 kg of plutonium. These stocks would be sufficient for perhaps 100–240 simple fission weapons based on HEU and 90 plutonium weapons, assuming 25 kg of HEU or 5 kg of plutonium per weapon. Pakistan could produce more weapons if it is able to mine more uranium or has developed more advanced weapon designs requiring less fissile material.

Pakistan could alternatively move to an arrangement where it uses its 40 tons a year of natural uranium production to fuel the three Khushab reactors, and then enriches the reprocessed uranium from their spent fuel to make HEU. This can be accomplished with an enrichment capacity of 30,000 SWU, for tails of 0.3 percent. This arrangement could in principle last for the lifetime of the Khushab reactors, as long as Pakistan can produce at least 40 tons of uranium a year, and would yield 35 kg of plutonium and 140 kg of HEU per year. In this scenario, much larger enrichment capacities would remain underutilized.

NOTES AND REFERENCES

1. See for example, Nuclear Energy Agency, Organisation for Economic Co-operation and Development, *Uranium 2007: Resources Production and Demand*. (Vienna: OECD Publishing, 2008). Published biennially, this report is commonly referred to as the "Red Book" and this term is used to reference many of the biennial reports throughout this paper.

2. Annual estimates of global and national fissile material production and stocks are reported by the International Panel on Fissile Materials. The most recent report is "Global Fissile Material Report 2008, Scope and Verification of a Fissile Material (Cutoff) Treaty," <http://www.fissilematerials.org/ipfm/pages_us_en/documents/documents/documents.php> (accessed August 2009).

3. Z. Mian and A. H. Nayyar, International Panel on Fissile Materials, "Pakistan and the FMCT," *Towards a Global Ban on the Production of Fissile Materials for Nuclear Weapons: Country Perspectives on the Challenges to a Fissile Material (Cutoff) Treaty*, 1 October 2008 <http://www.fissilematerials.org/ipfm/pages_us_en/documents/documents/documents.php> (accessed August 2009).

4. For an estimate of India's fissile material stocks up to 2020, see R. Rajaraman, "Estimates of India's Fissile Material Stocks," *Science and Global Security* 16(3) (2008): 74–86.

5. Nazir Ahmad, “The Pakistan Atomic Energy Commission,” *Pakistan Quarterly* 7(3) (1957): 14–17.

6. Mohamad Ashraf, “Uranium Prospecting in Pakistan,” *The Nucleus* 1(4) (1964): 28–30.

7. M.Y. Moghal, “Uranium in Siwalik Sandstones, Sulaiman Range, Pakistan, Formation of Ore Bodies” (Proceedings of A Symposium on the Formation of Uranium Ore Deposits, Athens, 6–10 May 1974), 383–403.

8. F.A. Shams, F. Barthel, and H. Fohse, *Geology of Pakistan*, ed. F.K. Bender and H.A. Raza. (Berlin: Gebruder Borntraeger, 1995), 222.

9. Organisation for Economic Co-operation and Development, Nuclear Energy Agency, *World Uranium Geology and Resource Potential: International Uranium Resources Evaluation Project* (San Francisco: Miller-Freeman Publications, 1980).

10. Muhammad Mansoor, “Nuclear Minerals in Pakistan,” *The Nucleus* 42(1–2) (2005): 73–83.

11. Dera Ghazi Khan, “Irregularities in PAEC’s project alleged,” *Dawn* (Pakistan), 27 March 1998.

12. International Atomic Energy Agency, Nuclear Fuel Cycle Information System, <http://www.iaea.org/OurWork/ST/NE/NEFW/nfcms_infcis_NFCIS.html> (accessed August 2008).

13. Azim Kidwai, “Search for Nuclear Minerals,” *Dawn* (Pakistan), 23 February 1979. This article quotes the Pakistan Atomic Energy Commission Annual Report.

14. Shahid-ur-Rehman, “Pakistanis tell of Indigenous U mining and Milling Effort,” *Nuclear Fuel*, 1 December 1986.

15. International Atomic Energy Agency, *Pakistan, Country Nuclear Fuel Cycle Profiles, Second Edition*, Technical Reports Series No. 425 (Vienna: International Atomic Energy Agency, 2005). <http://www-pub.iaea.org/MTCD/publications/PDF/TRS425_web.pdf> (accessed August, 2009).

16. Dera Ghazi Khan, “Irregularities in PAEC’s Project Alleged,” *Dawn* (Pakistan), 27 March 1998.

17. Nadeem Saeed, “Villagers’ Fears of Nuclear Waste,” *BBC*, 28 April 2006, <news.bbc.co.uk/2/hi/south_asia/4954730.stm> (17 August 2009).

18. International Atomic Energy Agency, World Distribution of Uranium Deposits (UDEPO) Database, <http://nucleus.iaea.org/NUCLEUS/nucleus/Content/CatalogueOfInformationResources/Nuclear_Fuel_Cycle_and_Fuel_Materials/World_Distribution_of_Uranium_Deposits.html> (accessed August 2008).

19. Muhammad Mansoor, “Nuclear Minerals in Pakistan,” *The Nucleus*, 42(1–2) (2005): 73–83.

20. *Op. cit*, International Atomic Energy Agency.

21. The Table uses “Red Book” estimates for Pakistan reported in 1990, 1997, 1999, 2005, and 2007. These estimates were retrospectively increased to include production of 30 tons of uranium per year from 1971 to 1980 and continuing at this higher rate until 1991. Organisation for Economic Co-operation and Development, *Forty Years of Uranium Resources, Production, and Demand in Perspective, “The Red Book Retrospective”* (Vienna*: OECD, 2006*), Appendix 7.1, 256–257. No explanation is given in

"The Red Book Retrospective" for this revision. This increase is inconsistent, however, with reports from the Pakistan Atomic Energy Commission, that there was exploration and development but not large scale uranium mining in Pakistan between 1971 and 1980. See for example, *op cit*, Azim Kidwai, and *op. cit.* Muhammad Mansoor. We rely therefore on the original "Red Book" estimates rather than the revised figures offered in "The Red Book Retrospective." The "Red Book Retrospective" also shows an estimated production between 1980 and 2003 of 721 tons. This is 130 tons greater than the estimate shown here, which is based on individual Red Books.

22. Ihtasham ul Haque, "$600m Plan to Explore and Mine Uranium" *Dawn* (Pakistan)*,* 1 March 2007.

23. International Atomic Energy Agency Information Circular (INFCIRC), "Text of the Agreement of 2 March 1977 between the Agency and Pakistan for the Application of Safeguards in Connection with the supply of Uranium Concentrate," 248 (July 1977).

24. "If the Devil Asks (me) to Sell Him Uranium, Today, I'll Sell it to Him," *Nuclear Fuel*, 27 April 1981. Other reports suggest Pakistan imported 110 tons of uranium from Niger in 1979, which was declared and safeguarded. International Institute for Strategic Studies, Strategic Dossier, "Nuclear Black Markets: Pakistan, A.Q. Khan and the Rise of Proliferation Networks" (2007): 26.

25. It is claimed that Libya purchased 1212 tons of uranium from Niger and covertly supplied 200–300 tons of it to Pakistan. David K. Willis, "The Uranium Flow: Who Controls It?" *The Christian Science Monitor*, 2 December 1981. See also *op. cit,* International Institute for Strategic Studies.

26. The imports of uranium are reported in International Atomic Energy Agency, "Implementation of the NPT Safeguards Agreement in the Socialist People's Libyan Arab Jamahiriya, Report by the General Director," GOV/2004/59 (2004): 3, <www.iaea.org/Publications/Documents/Board/2004/gov2004–59.pdf> (accessed August 2009). The inventory verification is given in International Atomic Energy Agency, "Implementation of the NPT Safeguards Agreement in the Socialist People's Libyan Arab Jamahiriya," GOV/2008/39 (12 September 2008), Annex, 1, <www.iaea.org/Publications/Documents/Board/2008/gov2008–39.pdf> (accessed August 2009).

27. A. Q. Khan claims that in 1982 Pakistan received 10 tons of un-enriched uranium hexafluoride and 5 tons enriched to 3% along with 50 kg of weapon-grade HEU. Simon Henderson, "Nuclear Scandal-Dr. Abul Qadeer Khan," *The Sunday Times*, 20 September 2009, and R. Jeffrey Simith and Joby Warrick, "A Nuclear Powers Act of Proliferation," *Washington Post*, 13 November 2009.

28. S.M.N. Zaidi, "Making of N-Power Fuel in Pakistan," *The Nation,* 21 September 1990. KANUPP fuel was successfully produced in 1980.

29. KANUPP's original design equilibrium core average discharge burn up was initially 8650 MWd/t, but was recalculated in 1995 using modern reactor physics codes as 7400 MWd/t. Iqbal Ahmed, Waqar Butt, Zia ul Hasan Siddiqi, Javed Iqleem, "Plant Life Extension at Kanupp: An Update," *Nuclear Engineering International* (June 1997): 18–20.

30. Mark Hibbs, "After 30 Years, PAEC Fulfills Munir Khan's Plutonium Ambition," *Nucleonics Week*, 15 June 2000.

31. "Pakistan's Indigenous Nuclear Reactor Starts Up," *The Nation*, 13 April 1998.

32. "Pakistan is Reprocessing Fuel Rods to Create Plutonium Nuclear Weapons," *CBS* News Transcripts (6:30 PM ET), 16 March 2000. For further details, see Z. Mian and A.

H. Nayyar, "An Initial Analysis of ^{85}Kr Production and Dispersion from Reprocessing in India and Pakistan," *Science and Global Security* 10(3) (2002): 151–179.

33. The second Khushab reactor was reported in July 2006, see David Albright and Paul Brannan, "Commercial Satellite Imagery Suggests 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 (ISIS) 24 July 2006; and "U.S. Disputes Report on New Pakistan Reactor," *New York Times,* 3 August 2006. Images of the third reactor were released in June 2007. David Albright and Paul Brannan, "Pakistan Appears to be Building a Third Plutonium Production Reactor at Khushab Nuclear Site," Institute for Science and International Security (ISIS) (21 June 2007). The image in Figure 2 is from David Albright and Paul Brannan, "Update on Khushab Plutonium Production Reactor Construction Projects in Pakistan," Institute for Science and International Security (ISIS) 23 (April 2009).

34. David Albright and Paul Brannan, *op cit.,* "Pakistan Appears to be Building a Third Plutonium Production Reactor at Khushab Nuclear Site."

35. David Albright and Paul Brannan, "Second Khushab Plutonium Production Reactor Nears Completion," Institute For Science and International Security (ISIS) (18 September 2008).

36. David Albright and Paul Brannan, *op cit.,* "Commercial Satellite Imagery Suggests Pakistan is Building a Second, Much Larger Plutonium Production Reactor: Is South Asia Headed for a Dramatic Buildup in Nuclear Arsenals?"

37. A Pakistani official described the claim that Khushab-II had a 1000 MWt capacity as "highly exaggerated." Cited in Joby Warrick, "Pakistani Reactor not as Significant as was Reported, Administration Says," *Washington Post*, 5 August 2006.

38. David Albright and Paul Brannan have reduced their estimates from 1000 MWt down to about 100 MWt, op. cit., David Albright and Paul Brannan, "Second Khushab Plutonium Production Reactor Nears Completion." An estimate that Khushab II is "at least as large as the 40 MWt-Class Khushab I but less than that of the 100 MWt-Class DHRUVA reactor" is offered in Thomas Cochran "What is the Size of Khushab II?" National Resources Defense Council (September 2006).

39. The U.S. officials are cited in William J. Broad and David E. Sanger, "U.S. Disputes Report on New Pakistan Reactor," *New York Times*, 3 August 2006.

40. If Khushab II and III were to have a capacity as high as 100 MWt each, they would consume along with Khushab I a total of 65 tons of uranium per year.

41. David Albright, Paul Brannan, and Robert Kelley, "Pakistan Expanding Dera Ghazi Khan Nuclear Site: Time for U.S. to Call for Limits," Institute For Science and International Security (ISIS) (May 2009). The nuclear fuel fabrication site is at Kundian, near Chashma.

42. David Albright and Paul Brannan, "Pakistan Expanding Plutonium Separation Facility Near Rawalpindi," Imagery Brief, Institute For Science and International Security (ISIS) (May 2009).

43. David Albright and Paul Brannan, "Chashma Nuclear Site in Pakistan with Possible Reprocessing Plant," Imagery Brief, Institute For Science and International Security (January 2007).

44. See for instance David Albright, Frans Berkhout and William Walker, *Plutonium and Highly Enriched Uranium 1996* (New York: SIPRI/Oxford University Press, 1997), 462, table A.1.

45. Note that 1 fission = 207 MeV, where 1 eV = 1.6×10^{-19} J. Since 1 J = 1 Ws, it follows that 1MWh = 3.6×10^{9} J and therefore 1 MWh corresponds to 10^{20} fissions.

46. We are grateful to Alexander Glaser for sharing the results of his MCNP calculations on the isotopic composition of spent fuel from a low-burn-up 40 MWt heavy water reactor.

47. International Atomic Energy Agency, *Management of Reprocessed Uranium: Current Status and Future Prospects*, IAEA-TECDOC-1529 (2007), 17. The transuranic isotopes include Pu-238 Pu-239, Pu-240, Pu-241, Pu-242; Np-237; Am-241; Cm-242, Cm-244. The fission products include Zr-95/Nb-95; Ru-103, Ru-106; Cs-134, Cs-137; and Tc-99. The chemical impurities include boron, silicon, vanadium, tungsten, technetium, neptunium, ruthenium, chromium, and molybdenum.

48. Albright et al., *op cit,*. 32.

49. *Op. cit.,* Nuclear Energy Agency, Organisation for Economic Co-operation and Development, *Uranium 2007, Resources Production and Demand,* 80. The 2007 "Red Book" reports that "Uranium recovery through reprocessing of spent fuel, known as RepU, has been conducted in the past in several countries, including Belgium and Japan. It is now routinely done only in France and the Russian Federation, principally because recycling of RepU is a relatively costly endeavor, in part due to the requirement for dedicated conversion, enrichment and fabrication facilities." Reprocessed uranium has been re-enriched and used in PWR fuel by Germany, France, Japan, Russia, United Kingdom, United States, Belgium, Spain, Sweden and Switzerland. *Op cit.*, International Atomic Energy Agency, "Uranium: Current Status and Future Prospects." 17.

50. World Nuclear Association, "Processing of Used Nuclear Fuel" (March 2009). <http://www.world-nuclear.org/info/inf69.html> (accessed August 2009).

51. For U.S., see U.S. Department of Energy, National Nuclear Security Administration, "Highly Enriched Uranium: Striking a Balance; A Historical Report on the United States Highly Enriched Uranium Production, Acquisition, and Utilization Activities from 1945 through September 30, 1996," Revision 1 (2001), publicly released in 2006 <http://www.fissilematerials.org/ipfm/site_down/doe01.pdf> (accessed August 2009) and Lockheed Martin Energy Systems, Inc. Oak Ridge Y-12 Plant, "Initial Report on Characterization of Excess Highly Enriched Uranium, Nuclear Materials Management and Storage," Y/ES-086 (1996), <http://www.fissilematerials.org/ipfm/site_down/doe96b.pdf> (accessed August 2009). For the USSR, see Oleg Bukharin, "Analysis of the Size and Quality of Uranium Inventories in Russia," *Science and Global Security* 6(1) (1996): 59–77, and E.H. Gift, National Security Programs Office, Martin Marietta Energy Systems, Inc. "Analysis of HEU samples from the ULBA Metallurgical Plant," revised in 1995 by A. W. Riedy <http://www.osti.gov/bridge/purl.cover.jsp?purl=/192548-Ag02e9/webviewable/> (accessed September 2009).

52. Op cit., International Atomic Energy Agency, *Management of Reprocessed Uranium: Current Status and Future Prospects*, 32.

53. Samar Mubarakmand, in "Munir Ahmad Khan Memorial Reference*," Pakistan Military Consortium* (delivered by the speakers at the Memorial Reference held in the memory of Munir Ahmed on 28 October 2007 in Islamabad), <http://www.pakdef.info/pakmilitary/army/nuclear/memorial_munrahmed.html> (accessed August 2009).

54. Shahid-ur Rehman, *Long Road to Chagai* (Islamabad: Printwise Publications, 1999), 50.

55. “German Firm Cited in Case Involving Sale of Fluoride Conversion Plant to Pakistan,” *Nuclear Fuel*, 20 July 1981.

56. Shahid-ur Rehman, *op cit.,* 59.

57. “Qadeer Terms Acquiring of Nuclear Technology a Miracle,” *Dawn* (Pakistan)*,* 27 May 2001.

58. “N-capability Acquired in 1983, says Qadeer,” *Dawn* (Pakistan*),* 30 May 1999; Rauf Siddiqi “Khan Boasts Pakistan Mastered Uranium Enrichment by 1982,” *Nucleonics Week*, 20 May 1999.

59. “The Pakistan Nuclear Program,” declassified U.S. State Department briefing paper, <http://www.gwu.edu/˜nsarchiv/NSAEBB/NSAEBB6/ipn22_1.htm> (accessed August 2009). The term “significant quantity” for HEU normally refers to the International Atomic Energy Agency standard of 25 kg of material, the amount required for a simple first generation implosion fission weapon, but it may not have been used in this technical sense in the report.

60. Albright, Berkhout, and Walker *op cit.*, 274.

61. E. Koch, and S. Henderson, “Inside Kahuta,” *Foreign Report*, *The Economist* (May 1986) 275, fn. 65. The enrichment halls were identified as the two larger buildings on the left and right of the picture in a September 2005 U.S. State Department briefing, <http://abcnews.go.com/images/International/iran_nuclear_report.pdf> (accessed August 2009).

62. A. F. Ameen, quoted in S. Khan, “Fear of U.S. Aid Cutoff Said to Have Deterred Pakistan’s Bomb Program,” *Nuclear Fuel*, 11 August 1986.

63. Mark Hibbs, “Khan Network sought CNOR Bearings Long after KRL Gave up Centrifuge,” *Nuclear Fuel,* 26 September, 2005.

64. Anwar Iqbal, “Pakistan can Explode H-bomb: A Q Khan,” *The News International* (Pakistan), 30 May, 1998; “Nuclear Tests Ensured Country’s Impregnable Defense: Qadeer,” *The News International* (Pakistan), 27 May 2001.

65. National Security Archives, “U.S. Nuclear Non-proliferation Policy: *1945–91*,” Document no. 02328 (1992), quoted in Albright et al., *op cit.,* 273.

66. “A Bomb Ticks in Pakistan,” *New York Times Magazine*, 6 March 1988.

67. S. Levine, “Bhutto says Pakistan can Build Nuclear Weapons,” *The Guardian*, 2 September 1991.

68. “Summary of Substantial Facts*,” Charge Sheet, The State versus Daniel Geiges and Gerhard Wisser,”* High Court of South Africa, Transvaal Provincial Division, 2006, Sections 6.19 and 6.20.

69. Albright, et al. *op cit.*, 275. See also Mark Hibbs, “India and Pakistan Fail to Include New SWU Plants on Exchanged Lists,” *Nuclear Fuel*, 30 March 1992.

70. The Symington amendment was section 620(s) of the Foreign Assistance Act of 1967. The amendment required the President to withhold economic assistance if in his view the recipient country excessively and unnecessarily diverted resources to military expenditures. The Pressler Amendment was a new section 620(e) of the Foreign Assistance Act of 1985. Pressler prohibited U.S. assistance or military sales to Pakistan

unless annual Presidential certification was issued that Pakistan did not possess a nuclear explosive device.

71. Michael R. Gordon, “Congress Delays New Pakistan Aid amid Nuclear Rift,” *New York Times*, 30 September 1987.

72. M. Hussein, “Nuclear Issue: Ball is Now in Pakistan’s Court,” *The Nation* (Lahore), 29 November 1990.

73. R. Jeffrey Smith, “Pakistan Official Affirms Capacity For Nuclear Device; Foreign Minister Vows to Contain Technology,” *The Washington Post*, 7 February 1992.

74. In an interview with BBC “Hard Talk Pakistan” on 10 February, 2004, General Mirza Aslam Beg is reported as saying that “We brought it down from 95 per cent and above, which is weapons grade enrichment, to 5 per cent and below ... which is commercial grade enrichment. ... And if you know how the centrifuge works, if you want to go up to 95 per cent, you have to keep the machine running for another two weeks and you’ll have all the material you want.” Cited in “Pak Army Never Controlled Nuclear Programme: Mirza Aslam Beg,” *Rediff News,* February 11, 2004 <http://in.rediff.com/news/2004/feb/10pak2.htm> (accessed August 2009).

75. Mark Hibbs, “U.S. Now Believes Pakistan to Use Khushab Plutonium in Bomb Program,” *Nucleonics Week*, 16 July 1998. David Albright claims, “As of early 1998, Pakistan is not known to have resumed the production of HEU.” *Fact Sheet: India and Pakistan—Current and Potential Nuclear Arsenals*, 13 May 1998, <http://www.globalsecurity.org/wmd/library/news/pakistan/1998/980513-ISIS1.htm> (August 18, 2009).

76. “Nuclear Black Markets: Pakistan, A. Q. Khan and the Rise of Proliferation Networks,” International Institute of Strategic Studies, Strategic Dossier, London, 2007.

77. Mark Hibbs, “China Said Aiding Kahuta Project,” *Nucleonics Week*, 8 February 1996.

78. Mark Hibbs, “Pakistan Developed More Powerful Centrifuges,” *Nuclear Fuel*, 29 January 2007; Mark Hibbs, “P-4 Centrifuge Raised Intelligence Concerns about Post-1975 Data Theft,” *Nucleonics Week*, 15 February 2007.

79. David Albright, “ISIS Estimates of Unirradiated Fissile Material in De Facto Nuclear Weapon States, Produced in Nuclear Weapon Programs,” Institute for Science and International Security (April 2004), Revised June 2005.

80. Enrichment facilities at Sihala, Golra and Gadwal, described respectively as a “pilot plant,” “testing facility” and “enrichment plant,” are listed for instance in Joseph Cirincione, Jon. B. Wolfstal and Miriam Rajkumar, *Deadly Arsenals: Nuclear, Biological and Chemical Threats* (Washington D.C.: Carnegie Endowment for International Peace, 2005), 256–257. In 1998, the U.S. Department of Commerce listed “ultracentrifuge” facilities at Golra and Sihala, and an “enrichment plant” at Gadwal as subject to export restrictions. U.S. Department of Commerce, Bureau of Industry and Security, 15 CFR Part 742 and 744, *Federal Register*, vol. 63. No. 223, 19 November 1998, <http://www.bis.doc.gov/pdf/india-pakistanentities-nov98.pdf> (accessed August 2009).

81. On Gadwal as the site for enrichment to weapons-grade, see Jonathan Landay, “Despite Taliban Turmoil, Pakistan Expands Nuke Plants,” *McClatchy Newspapers*, 1 May 2009; <http://www.mcclatchydc.com/world/story/67379.html> (Accessed August 2009).

82. Sajid Chaudhry, "CDWP okays Rs 13.7bn N-fuel enrichment plant," *Daily Times*, 27 July 2007. The plant is intended to have an initial capacity of about 150,000 SWU per year, which will be expanded in three subsequent stages of 150,000 SWU/y each by 2030, for a total of 600,000 SWU.

83. Humayun Farshori, "National Energy Needs" (presentation to Pakistan Development Forum, 26 April 2005, Islamabad), <http://siteresources.worldbank.org/PAKISTANEXTN/Resources/293051–1114424648263/Session-VII-Energy.pdf> (accessed August 2009).

84. The Nuclear Suppliers Group export guidelines are at <www.nuclearsuppliersgroup.org/guide.htm> (accessed August 2009).

85. See, e.g., Allan S. Krass, Peter Boskma, Boelie Elzen and Wim A. Smit, *Uranium Enrichment and Nuclear Weapon Proliferation* (New York: Taylor and Francis, 1983).

86. Stripping down to tails of 0.1 percent is practiced for instance as part of the uranium enrichment activity by Rosatom, which produces depleted uranium tails containing 0.2 percent uranium-235 and then strips further down to tails of 0.1 percent. Oleg Bukharin, "Russia's Gaseous Centrifuge Technology and Uranium Enrichment Complex," Program on Science and Global Security Princeton University (January 2004), < www.ransac.org/Documents/bukharinrussianenrichmentcomplexjan2004.pdf> (accessed August 2009).

87. "Pakistan joins DU producer nations," *International Defense Digest* 34(5) (2001): 1.

88. *Op. cit.*, Organisation for Economic Co-operation and Development, *Forty Years of Uranium Resources, Production, and Demand in Perspective*. If there is an additional 130 tons of natural uranium that was produced between 1980 and 2003 as suggested, the natural uranium feed would last until 2009.

89. *Op. cit.*, Organisation for Economic Co-operation and Development, *Forty Years of Uranium Resources, Production, and Demand in Perspective*. Enriching an additional 130 tons of natural uranium, as suggested, would have produced additional depleted uranium which would in turn last as feed beyond 2020.

90. The additional 130 tons of natural uranium would mean that the natural uranium feed would last one more year.

91. International Atomic Energy Agency, "Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran," GOV/2004/83, 15 November 2004, 9.

92. International Atomic Energy Agency, "Implementation of the NPT Safeguards Agreement of the Socialist People's Libyan Arab Jamahiriya," GOV/2004/33, 28 May 2004, Annex 1, 5.