Uranium constraints in Pakistan: how many nuclear weapons does Pakistan have?

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It is generally accepted that Pakistan's nuclear weapons programme relies on domestic supplies of uranium. Although constraints on uranium supply in Pakistan are recognized, this is often not taken into account when estimating the amount of fissile material that Pakistan may have produced. In simple words, most assessments of Pakistan's fissile materials and arsenal size fail to look at the supply and demand situations in Pakistan in an integrated way. This paper attempts to rectify this lacuna by taking a combined look at the supply and demand situations for uranium in Pakistan. It specifically addresses issues of how shortages in supply or increases in demand will affect the allocation of available uranium resources for meeting various military and civilian needs.

Keywords: Fissile materials, highly enriched uranium, nuclear weapons, Pakistan, weapons grade plutonium.

PAKISTAN'S nuclear weapon capabilities and the size of its arsenal is a major area of international concern. The amount of fissile material that a country possesses, directly determines the number of nuclear weapons that it can make. The International Panel for Fissile Materials (IPFM), that provides data on the stockpile of fissile material held by various countries is the standard source used by analysts for estimating the size of Pakistan's nuclear arsenal. IPFM also provides periodic updates to its stockpile reports and their implications for the number of nuclear weapons.

The IPFM estimates that at the end of 2014, Pakistan had approximately 3100 kg of highly enriched uranium (HEU), and 190 kg of Weapons grade Plutonium (WgPu). In its earlier report of 2010, IPFM said that Pakistan had a stockpile of approximately 2600 kg of HEU and 100 kg of WgPu. This implies that Pakistan added 500 kg of HEU and 90 kg of WgPu in four years between 2010 and 2014.

According to IPFM, this translates into an arsenal of 120 to 130 warheads made up of both HEU and plutonium weapons as of end 2010. Most analysts studying the nuclear weapons programme in South Asia use these estimates to determine the number of warheads in Pakistan. This data is also widely used in most narratives on nuclear deterrence to reinforce the dangers of a nuclear arms race in the region.

As a trend, the IPFM estimates show that the amount of fissile materials in Pakistan is increasing. Though some researchers like Zia Mian[1] suggest that Pakistan could face uranium fuel constraints for their Khushab reactors, this does not seem to be factored into IPFM projections. The underlying assumption seems to be that Pakistan has adequate supplies of domestic uranium to meet all its needs.

While there could be problems with supply, there is no need to doubt that the demand for uranium has been increasing in Pakistan. One of the problems in estimating the size of Pakistan's nuclear arsenal has been that, most assessments of fissile materials and arsenal size fail to look at the supply and demand situations in Pakistan in an integrated way.

A major question that has continued to bother the Indian strategic community has been 'How much fissile material does Pakistan really possess'? Trying to find an answer to this question needs a number of other issues to be addressed. These are:

- The Karachi Nuclear Power Plant (KANUPP) electricity producing reactor began operations in 1971 and continues to work till today. Since 1980 it has depended on domestically produced fuel for its working. Can we estimate the amount of uranium that is needed for operating KANUPP on a continuing basis?
- Can we estimate the amount of HEU that Pakistan could have produced since the start of operations at the Kahuta enrichment facility?
- How much weapon grade plutonium has Pakistan produced since the start of the Khushab reactor complex in 1996?
- How much yellowcake has Pakistan produced[2]?
- Does Pakistan have enough uranium to meet its demands?

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The purpose of this study is to find an answer to each of these questions and then make an assessment of Pakistan's nuclear arsenal. The analysis presented here is based on publicly available information on Pakistan, together with a few assumptions. All our estimates are based on yellowcake (U_3O_8) requirements.

Estimating demand

There are three major facilities in Pakistan that need to be fed with domestically produced yellowcake. These are the KANUPP civilian reactor, the enrichment facility at Kahuta and the plutonium production reactors at the Khushab complex. While the KANUPP reactor is under safeguards, the Kahuta complex and the Khushab reactors are outside the purview of safeguards.

The enrichment facility in Kahuta started operations in 1984. There is a lot of uncertainty about the number and type of centrifuges housed within this facility. Some assumptions are therefore needed for estimating the demand. Though Pakistan probably has more than one enrichment facility, we will only consider the major facility at Kahuta. Additional enrichment facilities would only mean that the demand for yellowcake would increase. Our demand estimates are in that sense quite conservative and the actual demand may be even higher.

The Khushab complex has four plutonium reactors referred to as K1, K2, K3 and K4. All of them are identical. K1 began operations in 1996, K2 in 2010, K3 in 2013 and K4 in 2015.

KANUPP reactor demand

Pakistan began construction of its first Nuclear Power Plant (NPP), KANUPP, in 1966 at Karachi. The plant was connected to the national grid on 18 October 1971. KANUPP, a Canadian Deuterium Uranium (CANDU) design reactor of 137 MW was constructed by Canadian General Electric (CGE) under a turnkey contract.

After India's first nuclear test of 1974, Canada withdrew support and cut off fuel supplies to KANUPP in 1976. The Pakistan Atomic Energy Commission (PAEC) then undertook the manufacture of some spares and fuel rods on an emergency basis. KANUPP has been using domestic fuel since 1980. Though KANUPP uses indigenously developed fuel elements, it continues to operate under International Atomic Energy Agency (IAEA) safeguards[3].

There are different ways of estimating the amount of fuel required for a nuclear reactor of the KANUPP type. Ideally if we know the total number of fuel bundles loaded in the reactor, then a straightforward estimate of the fuel could be obtained. This is rarely available. If we knew the effective full power days of operation, then an estimate of the fuel required could be obtained assuming other reactor characteristics. Another standard method of calculating the fuel required is based on the installed electric capacity, the number of days of operation, thermal efficiency and the burn-up rate[4].

The fuel needed for KANUPP reactor depends on reactor power, the capacity factor and the fuel burn-up. The KANUPP reactor is designed for a high burn-up (average 7500 MWt.d/ton) with the fuel staying in the reactor for more than a year. It is possible to estimate the fuel required for such a reactor by assuming the burn-up, the thermal efficiency, the number of days of operation and the cumulative generation of thermal energy that is available from the IAEA data[5].

The effective full power years (EFPY) of KANUPP by end 2002 amounted to only 10.8 according to PakAtom, a Newsletter of PAEC put out in January–February 2003. This would mean that KANUPP on an average operated for only 150 days in a year. Hence for our purpose, we calculate the fuel requirement for 150 days.

Using the Power Reactor Information System (PRIS)[6] data base, we estimate that the total amount of yellowcake required to fuel KANUPP for the period 1980–2014 is 805 tonnes. This is based on an average of 150 operating days in a year.

Demand by Kahuta enrichment plant

The primary Pakistani fissile-material production facility is located at Kahuta. It uses gas centrifuge enrichment technology to produce HEU. This facility started operating in 1984. The amount of feed required for an enrichment plant will depend on the Separative Work Unit (SWU) available, the type of centrifuges used, the percentage of enrichment desired, and the percentage of tailings. For Pakistan many of these characteristics are unknown. Yet, estimates of the cumulative amount of HEU are available in open source literature. One of the IPFM reports estimates that Pakistan could have produced 1750 kg of HEU over a period of thirty years. This is equivalent to producing 58 kg of HEU annually. By assuming different SWU values and different tailings percentages, the feed required to produce 58 kg of HEU annually[7] can be calculated. Table 1 shows the possible scenarios.

From Table 1, we can see that an amount of 58 kg of HEU can be obtained with a capacity of 13,000 SWU at 0.2% tails, or with a capacity of 11,000 SWU at 0.3% tails or with a capacity of 9000 SWU at 0.5% tails. The corresponding feed for these cases will be 10, 12 and 25 tonnes respectively. For our calculations, we assume a HEU product with a 0.3% tails. A capacity of 11,000 SWU with a tailing fraction of 0.3% will produce about 57 kg of HEU. The uranium feed required for achieving this is 12.4 tonnes. This is equivalent to a feed of 15.5 tonnes of yellowcake annually. On this basis the yellowcake

Table 1. Feed–product from an enrichment plant for different SWU

	0.2% Tails		0.3% Tails		0.5% Tails	
SWU (kg)	Feed (tonnes)	Product (kg)	Feed (tonnes)	Product (kg)	Feed (tonnes)	Product (kg)
9000	7.0	39.6	10.2	46.6	24.8	58.4
10,000	7.7	44.0	11.3	51.8	27.5	64.9
11,000	8.5	48.4	12.4	57.0	30.3	71.4
12,000	9.3	52.8	13.6	62.2	33.0	77.9
13,000	10.1	57.2	14.7	67.4	35.8	84.3

Table 2. Estimated annual yellowcake demand in Pakistan

Facility	Period	Annual demand (tonnes)	Cumulative demand (tonnes)	Assumptions
KANUPP	1980–2014	23.0	805	7500 MWd/T burn up, 150 days operation, 30% efficiency
Kahuta	1984–2014	15.5	481	SWU – 11000 kg/ year, 0.3% tailings, product HEU 57 kg average per year
Khushab 1	1996–2014	23.0	437	Capacity 50 MWt, burn up 1 MWd/kg, 100% reactor availability
Khushab 2	2010–2014	23.0	115	Capacity 50 MWt, burn up 1 MWd/kg, 100% reactor availability
Khushab 3	2013–2014	23.0	46	Capacity 50 MWt, burn up 1 MWd/kg, 100% reactor availability
Total	1980–2014		1884	Total demand – civilian and military uses

demand for enrichment purposes works out to be 481 tonnes for the period 1984–2014.

Demand from the Khushab plutonium production reactors

Khushab reactors also rely exclusively on domestic natural uranium. They are heavy water natural uranium reactors with a capacity of approximately 50 MWt. Since they are dedicated reactors for producing plutonium, they will operate with a low burn-up of 1000 MWd/T (ref. 8). Our estimate for this burn-up and the rated power capacity is that each Khushab reactor will need 18.25 tonnes of natural uranium or about 23 tonnes of yellowcake per year assuming a reactor availability of 100%. Pakistan started the first Khushab reactor in 1996. The second came up in 2010, the third in 2013 and the fourth in 2015. All the four reactors are identical. Therefore the feed requirements are expected to be the same. For the period 1996–2014 this translates into 26 reactor years of operations. Assuming that each reactor is fuelled once a year, Pakistan required 598 tonnes of yellowcake for operating these reactors till 2014.

Overall demand

The total demand for yellowcake in Pakistan to operate these three facilities till the end of 2014 thus works out to be 1884 tonnes. The demand scenario is summarized in Table 2.

Uranium supply in Pakistan

Assuming an uranium ore grade of 0.05% and a milling capacity of 300 tonnes of ore per day in Dera Ghazi Khan, we estimate that Pakistan could have produced 54 tonnes of yellowcake annually during the period 1980–2005. This is probably the maximum amount of yellowcake that Pakistan could have produced. Actual production may be less, because ore grades of Pakistan uranium deposits are likely to be even lower than what we have assumed.

Although the Bagalchur mine closed in 2000, we expect that the mill would have processed the ores for another five years. On this basis one would expect Pakistan to have a cumulative supply of 1405 tonnes of yellowcake[9] from the Bagalchur mine.

Pakistan also procured 110 tonnes of yellowcake from Niger in the seventies and produces some yellowcake from the three ISL mines[10] located at Qabul Khel, Nangar Nai and Taunsa. Adding all these together, the cumulative (total) amount of yellowcake available in Pakistan till 2014 has been estimated to be 1584 tonnes.

Matching supply and demand (1980–2014)

Assuming that KANUPP operated for 150 days a year on an average, the total (cumulative) demand for yellowcake in Pakistan to feed the three facilities mentioned above is 1884 tonnes. As against this demand, Pakistan would have produced 1584 tonnes of yellowcake cumulatively till 2014.

Figure 1 shows the curves of cumulative supply and demand for yellowcake for the period 1980–2014. Figure 1 also provides a timeline of major events that could have affected the supply demand equations for uranium in Pakistan. Other geo-political factors such as the fissile materials cut-off treaty (FMCT) that could affect the allocation of available uranium resources amongst conflicting demands are also indicated in Figure 1.

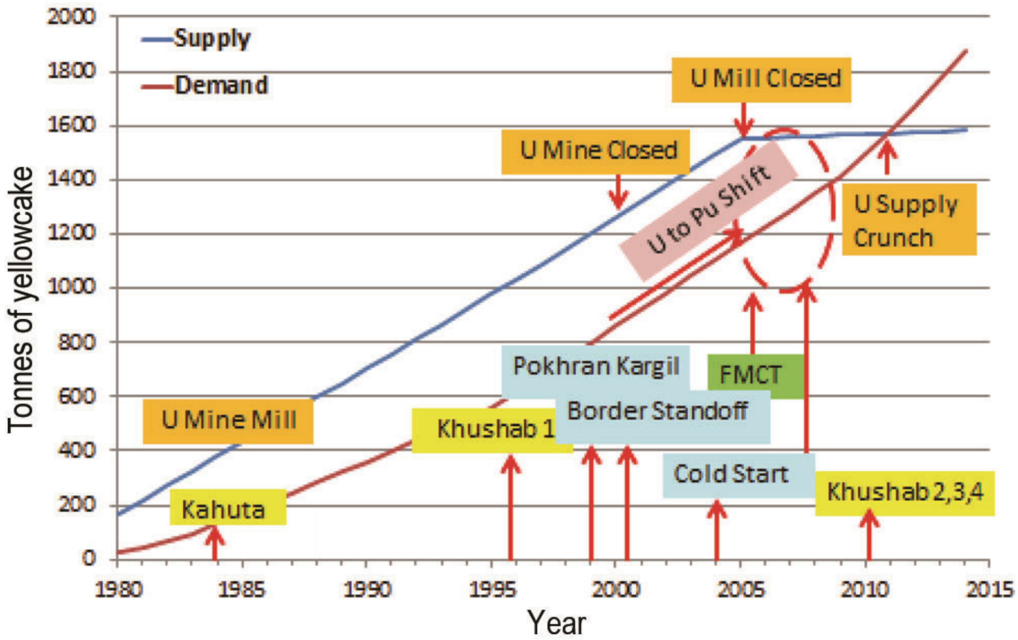

Figure 1. Cumulative uranium supply and demand scenario in Pakistan (1980–2014).

We can see from Figure 1 that there is a steady supply of yellowcake between 1980 and 2005, after which the supply curve reaches a plateau. An inflexion in the curve in 2005 depicts this. This is due to the closure of the Bagalchur uranium mine in 2000 and the end of milling operations at Dera Ghazi Khan in 2005.

There is an inflexion in the demand curve in 1996, which is the start of the operation of the first Khushab reactor. Between 1996 and 2005, Pakistan required about 40 tonnes of yellowcake annually for its weapons programmes, which was met by domestic supply. The figure also clearly shows that from 2010, the cumulative demand curve overtakes the cumulative supply curve creating a supply crunch. The problems in uranium supply began in 2005 and became severe from 2010.

It is quite likely that this emerging supply constraint was anticipated by Pakistani decision makers. One would therefore expect them to take steps to minimize the impact of these shortages on their key weapons programmes. The allocation of available yellowcake amongst the three programmes therefore becomes a critical factor in the determination of the arsenal size.

KANUPP – high priority demand

The production of electricity in a power short economy will obviously be a very high priority. The KANUPP civilian reactor would have needed 805 tonnes of yellowcake for its continuing operations till the end of 2014. After taking it out as a high priority need Pakistan would have been left with 780 tonnes of yellowcake for use in its weapons programme.

Choice between HEU and plutonium

The available yellowcake after taking out the demand from the civilian KANUPP electricity producing reactor had to be distributed between the production of HEU and plutonium.

The enrichment programme is older and started in 1984. Since Pakistan has only tested HEU weapons, the production of HEU to build up an arsenal would have been a high priority activity for quite some time. Till the start of the first Khushab reactor in 1996, it would have remained the only major demand. It would have continued to be important after the 1998 tests also, since HEU would be needed for building an arsenal. However since enough yellowcake is available to feed both the enrichment facility as well as the single operational Khushab reactor, one would expect that the demands of both would be met from the yellowcake inventory[11].

The Kargil crisis, Operation Parakaram and India's Cold Start Doctrine would have forced a rethink amongst Pakistan's strategic thinkers on the role of nuclear weapons in the prevention and deterrence of war. The need for developing plutonium-based tactical weapons would have become a major priority. The discussions on the Fissile Material Cut-off Treaty in Geneva that became more prominent after 2005 may have also had a role in Pakistan's decision to increase development focus on plutonium weapons. The decision on the second Khushab reactor followed by the setting up of a third and fourth reactors provides concrete evidence of this shift in focus. We can presume that the priority shifted from HEU and Kahuta decisively towards plutonium and the Khushab reactors around 2005. This would imply a token allocation of

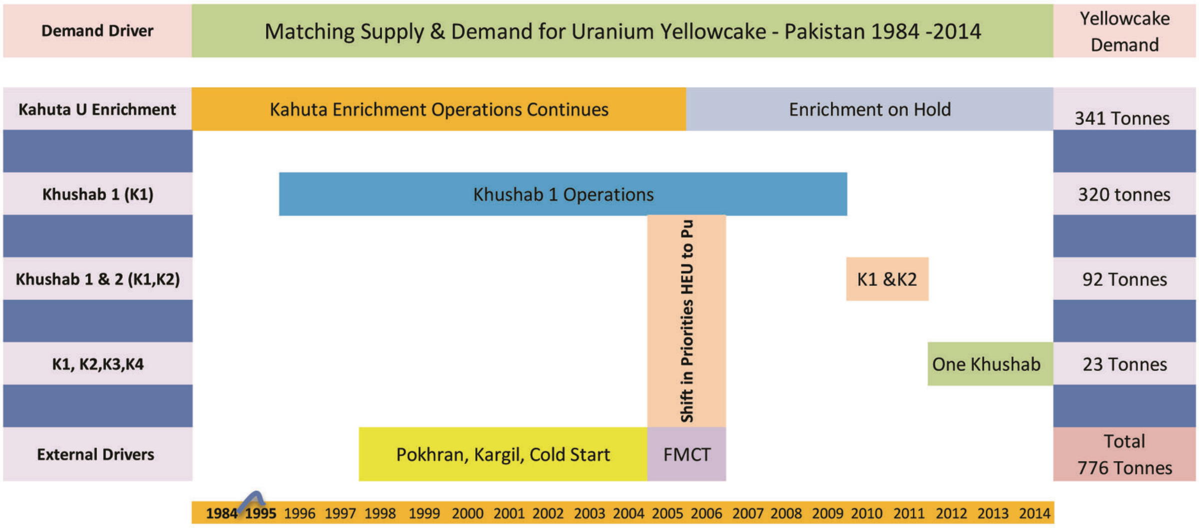

Figure 2. Distribution of yellowcake for HEU and plutonium production.

yellowcake to keep the Kahuta enrichment facilities ticking 2005 onwards with the bulk of yellowcake resources conserved or used for plutonium production. Figure 2 reflects the distribution of the yellowcake resources available for the weapons programme based on this revised allocation of priorities.

Figure 2 makes it clear that after the concurrent operation of the Khushab 1 and Khushab 2 reactors for 2010 and 2011, Pakistan would have again faced a uranium supply side crunch by 2012.

From 2012 onwards even after the setting up of the fourth Khushab reactor in 2015, Pakistan would only have had sufficient Uranium supplies to feed one of the Khushab reactors every two to three years. Any estimates of arsenal size would have to take into account this shift in priorities from HEU to Plutonium, as well as the possibility, that Pakistan would have a serious shortage of uranium yellowcake to feed its growing demands for nuclear weapons.

Pakistan's stockpile of HEU and WgPu

If we take the scenario outlined in Figure 2, where enrichment was carried out continuously from 1984 to 2005 and stopped thereafter, the amount of HEU in Pakistan amounts to 1254 kg. Since under this scenario, no significant quantities of yellowcake would be made available for enrichment after 2005, this would be the total stock of HEU available with Pakistan for production of nuclear weapons.

Assuming a cooling period of two years for the spent fuel from the Khushab reactors, it can be estimated that Khushab 1 would have produced 15.5 kg of WgPu annually from 1998. This reactor would have continued to operate on a continuous basis till 2011.

The second Khushab reactor became operational in 2010 and would have operated concurrently with the Khushab 1 reactor in 2010 and 2011. The fuel from this reactor too would have become available in 2012 and 2013 after a cooling of period of two years.

By 2012, the available supply of yellowcake was not enough to fuel even one of the Khushab reactors. One would have to wait till 2014 for enough fuel to accumulate before one of the four Khushab reactors could be operated. It is likely that the plutonium from one reactor would become available to the weapons programme before our cut-off date of 2014 for estimation of the arsenal size.

According to this scenario Pakistan could have accumulated 295 kg of weapon grade plutonium from all the Khushab reactors by 2014. This estimate represents the amount of weapons-grade plutonium present in the spent nuclear fuel and not the actual amount of weapons grade plutonium available after reprocessing. If we assume a reprocessing and recovery efficiency of 70% (ref. 12) for the irradiated fuel from the reactors, the estimated amount of plutonium for the period 1996–2014, would be 206 kg.

Based on this assessment we estimate that the amount of HEU available with Pakistan at the end of 2014 is 1254 kg. The amount of weapon grade plutonium that Pakistan possessed as of 2014 end is estimated to be 206 kg.

Pakistan's nuclear arsenal

Table 3 provides estimates of the arsenal size as of end 2014. Here we have considered the scenario where both enrichment and plutonium production operations progressed till 2010 leading to an accumulation of 1482 kg

Table 3. Estimates of nuclear weapons in Pakistan

	HEU weapons		Plutonium weapons		
	18 kg per weapon	12 kg per weapon	6 kg per Weapon	4 kg per weapon	Total weapons
This paper (2014)	78	104	34	52	112–156
Kristensen (2014)	172	258	32	48	204–306

of HEU and 154 kg of weapon grade plutonium. The non-availability of yellowcake beyond 2010 makes it imperative that these estimates of nuclear weapons are valid as of 2014. The HEU arsenal is based on the use of 12–18 kg of HEU per weapon. The plutonium arsenal is based on the use of 4–6 kg of plutonium per weapon. These are the same range of values as used by Kristensen and Norris[13] in their assessment of Pakistan's nuclear arsenal. Table 3 provides their estimates as well to facilitate easy comparisons[14].

As we can see from Table 3 our estimates are significantly lower than those provided by Kristensen and Norris[13]. We believe that because of uranium shortages, Pakistan's nuclear arsenal has reached a plateau and can only grow very slowly. Any alternative explanation for an increased arsenal size should provide a satisfactory and consistent explanation for uranium sourcing by Pakistan.

If we were to go with the scenario described in Figure 2, where the enrichment process is put on hold in 2005, the HEU arsenal size will be even smaller without significant increase in the number of plutonium weapons. With 1254 kg of HEU and 206 kg of weapon grade plutonium, Pakistan could have a total of 104 to 156 weapons of both kinds.

It is evident that if Pakistan wants to increase its arsenal; it makes more sense for Pakistan to go for HEU weapons especially when there is a uranium constraint. For tactical use, it may still need to miniaturize and therefore a plutonium base for nuclear weapons may also be needed. In spite of this logic, one has to question the credibility as to why Pakistan chose to build and operate four Khushab reactors to feed its nuclear weapons programme.

Implications

(i) The available evidence suggests that Pakistan has severe uranium constraints and could not have pursued both the HEU and the plutonium routes as vigorously as is generally believed.

(ii) In a business-as-usual scenario, the constraint appears to have become serious in year 2010. It is likely that Pakistani decision-makers would have become aware of this emerging shortage and acted to minimize its impact on the weapons programme. The Kargil crisis, Operation Parakram, India's Cold Start Doctrine and negotiations in Geneva on the FMCT would have also forced Pakistan to review its nuclear weapons programme. It is most likely that under these circumstances there was a shift in focus from HEU weapons to plutonium-based weapons. This would have entailed a reduction in the production of HEU and an increase in the production of plutonium around 2006.

(iii) In our assessment, Pakistan would have accumulated 1254 kg of HEU by the end of 2014. The corresponding IPFM estimate for HEU in Pakistan is 2700 kg by the end of 2014.

(iv) Correspondingly, the available Pu in spent fuel is estimated to be 295 kg. After taking into account the reprocessing efficiency (70%), our estimate of weapon grade plutonium works out to be 206 kg. According to Feiveson *et al.*[15], as of the end of 2012, Pakistan could have produced 100–200 kg of weapon grade plutonium. IPFM estimates that by the end of 2014, Pakistan would have accumulated 190 kg of WgPu.

(v) It is possible that Pakistan may be operating the enrichment facility to stockpile low enriched uranium (LEU 20%), for quick conversion to HEU at a later stage. If this were so, the HEU amounts in Pakistan would be even less than what we have estimated and therefore the arsenal would be even smaller.

(vi) The IPFM report of 2008 mentions the possibility of Pakistan's enrichment programme facing the brunt of shortages when the Khushab reactors go online. To quote[16]:

> 'Pakistan's annual HEU production capacity is constrained, however, by its limited domestic production of natural uranium (currently about 40 tonnes per year) and the need to also fuel its Khushab plutonium production reactor, which requires about 13 tonnes per year. This natural uranium constraint will become more significant when the second and third production reactors at Khushab come online. The three reactors will then require virtually all of the natural uranium that Pakistan produces.' These constraints are, however, not reflected in the subsequent estimates of fissile materials in Pakistan.

(vii) We estimate that Pakistan could at best have a total of between 112 and 156 nuclear weapons. Of this, about 78–104 would be HEU weapons and 34–52 would be plutonium weapons. This estimate is significantly lower than the estimates available in public domain.

(viii) In the analysis presented, the weak link is the amount of fuel required by KANUPP. If we were to assume that the number of operating days of working as 100 instead of 150 days assumed earlier, the total amount of fuel demand will be 537 tonnes. This suggests that Pakistan would have an additional 268 tonnes of yellowcake available for its weapons programme. What would this mean in terms of the nuclear arsenal? Firstly, the enrichment facility can run for three more years along with Khushabs 1, 2 and 3. Equivalently the number of HEU weapons would become 90–120 as against 78–104 estimated earlier. The number of plutonium weapons would be 50–78 as against 34–52 estimated earlier. Essentially, the constraint on uranium merely gets postponed by a few years and does not go away.

(ix) Despite these constraints, if Pakistan is indeed producing the amount of fissile materials as reported in the open source literature, the question of Pakistan's uranium sourcing especially after 2010 has to be addressed. Without a deeper understanding of this sourcing, it is difficult to believe that Pakistan has the arsenal it is reported to possess.

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9. For computational purposes we have taken the annual yellowcake production to be 54 tonnes.
10. Uranium deposits potentially amenable to uranium extraction by *in situ* leaching (ISL) technique were identified in the Siwalik sandstone near the village of Qabul Khel in the north-west frontier province of Pakistan. The production capacity of this ISL mine is estimated to be 2 tonnes annually. See *in situ* leach uranium mining: an overview of operations', International Atomic Energy Agency, November 2016; http://wwwpub.iaea.org/MTCD/Publications/PDF/P1741_web.pdf. Pakistan is also reported to have started in-situ leaching at Nanganai in 1996 and Taunsa in 2004. Production capacity of 1 T yellowcake per year is reported for each of these facilities. See TRS425, IAEA Document, p. 20.
11. This period also saw a lot of rivalry between the A. Q. Khan led Khan Research Laboratories and the Pakistan Atomic Energy Commission (PAEC). This would have also possibly contributed to a more equitable distribution of Uranium resources.
12. Recovery efficiency of plutonium is quoted as more than 95% in most literature; this however, refers to only the solvent extraction stage. Losses in the recovery during the stages prior to the solvent extraction and the later stages when taken into account would put the recovery efficiency closer to 70%.
13. Kristensen, H. M. and Norris, R. S., Pakistani nuclear forces. *Bull. Atom. Sci.*, 2016, **72**(6), 368–376.
14. A quick estimate of Pakistan's weapon arsenal can be got by noting that 3363 kg of YC is required for one HEU weapon assuming 15 kg of HEU per weapon. Similarly, 7600 kg of yellowcake is required per plutonium weapon assuming 5 kg per Plutonium weapon. If Pakistan were to convert all the available yellowcake (780 tonnes) to HEU weapons, it will have 232 HEU weapons. Alternatively, if all the yellowcake were to be converted to Pu weapons, it would have 103 Pu weapons.
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