Pakistan's Inventory of Weapon-Grade Uranium and Weapon-Grade Plutonium Dedicated to Nuclear Weapons[1]

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Summary

Pakistan is widely perceived to have the fastest growing nuclear weapons arsenal in the world. To that end, Pakistan has created a large infrastructure to make nuclear weapons from weapon-grade uranium (WGU) and plutonium. Its growing arsenal has sparked concerns about an increase in the chance that a miscalculation could lead to nuclear war in South Asia and about the adequacy of the security over these weapons and stocks of nuclear explosive materials against theft by terrorists.

To better understand this growing nuclear arsenal, this report assesses the size of Pakistan's stock of WGU and plutonium and the number of weapons that could be built from these materials as of the end of 2014. This task is complicated by the great lengths taken by Pakistan to conceal its quantity of nuclear weapons and the amount of plutonium and WGU it has produced for those weapons. Its formal policy is to maintain ambiguity about these key values.[2]

Pakistan's first nuclear weapon dates to about 1984. Its first weapons used weapon-grade uranium and nuclear weapon design data provided by China.[3] Meanwhile, Pakistan brought into operation a gas centrifuge plant at the Kahuta facility near Islamabad that could make weapon-grade uranium. In the 1980s, Pakistan designed its weapons so that they would not require full-scale testing, which allowed it to create a small arsenal while denying having nuclear weapons. This step was necessary to avoid the triggering of U.S. economic and military sanctions under U.S. law. Although the United States first sought to stop Pakistan's nuclear weapons program in the 1970s, it largely abandoned that effort following the Soviet Union's invasion of Afghanistan in 1979, focusing instead on mustering proxy fighters on Pakistan's territory to battle the Soviets in Afghanistan. As a result, in the 1980s, the Reagan and then the Bush administration often turned a blind eye to Pakistan's nuclear weapons program, despite Congressional pressure not to do so.

Pakistan maintained an ambiguous nuclear weapons posture until India conducted its nuclear tests in 1998. Soon afterwards, Pakistan detonated six weapons at two nuclear test sites and proclaimed

[1] This report is part of a series on national and global stocks of nuclear explosive materials in both civil and military nuclear programs. This project was generously funded by a grant from the Nuclear Threat Initiative.
[2] See for example, "A Conversation with Gen. Khalid Kidwai," Carnegie International Nuclear Policy Conference 2015, March 23, 2015.
[3] Albright, *Peddling Peril* (New York: Free Press, 2010).

that it was a nuclear power. Since 1998, it has sought to significantly expand its nuclear arsenal, focusing on increasing the number and sophistication of its weapons.

Pakistan's nuclear strategy places a great premium on keeping secret the location of its nuclear weapons and forces, fearing a preemptive Indian conventional military strike that could decapitate its nuclear forces. As part of that strategy, it keeps secret information about the number of its nuclear weapons, the quantity of its nuclear explosive materials, and its capabilities to make those weapons and materials. On a political level, Pakistan uses its nuclear weapons to assert its equality with its more powerful neighbor, which has motivated a further reluctance to reveal accurate estimates about its nuclear weapons.

As a result, little official information is available about Pakistan's nuclear weapons and the facilities engaged in making them. Despite this lack of official information, this report uses available information to estimate the size of Pakistan's stocks of weapon-grade uranium and weapon-grade plutonium dedicated to military purposes and the number of weapons' equivalent that could be built from these nuclear explosive materials. Pakistan's WGU stock is part of a larger stock of highly enriched uranium, where WGU is defined as HEU enriched over 90 percent and HEU includes all uranium enriched above 20 percent. This non-WGU highly enriched uranium is not estimated here, and much of it is believed to be an intermediate stock generated as WGU is produced. Pakistan also has a relatively large stock of civil plutonium that is addressed in another ISIS report assessing the size of national plutonium stocks at the end of 2014.

This study draws upon earlier ISIS studies (available at www.isis-online.org), commercial satellite imagery, decades of media reporting on Pakistan, and declassified documents about Pakistan's nuclear weapons program. As important, these estimates depend on information learned as a result of Pakistan's actions abroad to gain the wherewithal for building nuclear weapons and the Khan network's activities to spread nuclear weapons capabilities to other countries.

Pakistan has been heavily dependent on outside supply for many key direct- and dual-use goods for its nuclear programs. It maintains smuggling networks and entities willing to break supplier country laws to obtain these goods. Many of these illegal imports have been detected and stopped. These illegal procurements have led to investigations and prosecutions in the supplier states, leading to revelations of important details about Pakistan's complex to make nuclear explosive materials and nuclear weapons. This study has benefited greatly from this information.

A central figure in Pakistan's smuggling efforts was A.Q. Khan, considered by many as the father of the Pakistani bomb. With his transnational smuggling network, he greatly advanced Pakistan's nuclear efforts, obtaining from abroad the technology and goods to create the Kahuta gas centrifuge plant in a country with almost no indigenous industrial capabilities. But he went much further.

The Khan network also proliferated gas centrifuge and nuclear weapons technology to other countries, providing substantial assistance to Libya, Iran, and North Korea and attempting to sell aid to Iraq, South Africa, Syria, and perhaps others.[4] By the late 1990s, stopping Khan became a priority of Britain and the United States. Following the disruption of Khan's network in 2003 and 2004, the International Atomic Energy Agency (IAEA) conducted ground-breaking examinations

[4] *Peddling Peril*, op. cit.

into the inner workings of the Khan network on four continents. Moreover, national prosecutions of key network members in Germany, Switzerland, Malaysia, and South Africa uncovered many new details about the network's activities. Besides revealing the schemes of the Khan network, these investigations and prosecutions revealed important data about the Pakistani nuclear weapons program, in particular its uranium enrichment and nuclear weaponization programs. Information from these investigations is an important source for this report.

Despite opposition from much of the world, Pakistan has through its smuggling operations, determined efforts, and ingenuity, built a relatively large nuclear weapons production complex. Most of Pakistan's nuclear weapons are believed to use weapon-grade uranium, although increasingly its planned deployment of large numbers of short-range missiles and submarine launched missiles has required the further miniaturization of nuclear warheads, a process that favors plutonium. Its current materials production complex can produce significant amounts of both WGU and weapon-grade plutonium.

In summary, Pakistan is estimated to have produced the following quantities of plutonium and weapon-grade uranium for nuclear weapons through 2014.

	Pakistan's Military Fissile Material Stocks, end of 2014 (kg)	
	Median	**Range**
Plutonium	205	185-230
Weapon Grade Uranium	3,080	2,880-3,290

It is unclear how Pakistan uses plutonium and WGU in its nuclear weapons. An estimate of Pakistan's nuclear arsenal can be derived by assuming that the weapons use either WGU or plutonium but not both. The following table summarizes the nuclear weapons equivalent of these amounts of materials. Pakistan is unlikely to have built all those weapons. With requirements for plutonium and WGU in the weapons production pipeline and in reserves, it is assumed that only about 70 percent of these materials are in nuclear weapons. The number of nuclear weapons made from WGU and plutonium at the end of 2014, or about 125 to 170.

Estimated Number of Nuclear Weapons, Equivalent and Built through 2014		
	Nuclear Weapons Equivalent	**Nuclear Weapons Built**
Plutonium Only	50 (median)	35(median)
WGU Only	155 (median)	110 (median)
Total	205 (range: 180-245)	145 (range: 125-170)

Weapon-Grade Uranium Inventory, end of 2014

Pakistan's weapon-grade uranium is produced at two main sites. Pakistan's main source of enriched uranium is the Kahuta site, named Khan Research Laboratories (KRL), near Rawalpindi. Another major centrifuge site is located at Gadwal near Wah. The second site, according to a knowledgeable U.S. official, is primarily used to top off the enrichment level to weapon-grade. However, the scarceness of public information on the Gadwal site creates uncertainties about its purpose and size today.

Estimating the number and output of Pakistani centrifuges remains difficult. Pakistan has built thousands of centrifuges of varying types, all of which are based on designs Khan stole in Europe in the mid-1970s. Many of these centrifuges performed poorly or were replaced by more advanced models developed in KRL's centrifuge development facilities. Currently deployed designs are at least five to ten times more powerful than the initial centrifuges installed at Kahuta in the early 1980s, when it was deploying the inefficient P1 centrifuge, based on Dutch designs Khan stole in the Netherlands in the 1970s.

Gas Centrifuges

Key to estimating Pakistan's stock of WGU is developing a model of its gas centrifuge deployments and the performance of these centrifuges. Khan and his colleagues did not have an easy time getting the centrifuges to work, despite the enormous boost provided by purloining so much classified and sensitive European centrifuge technology and finding technically capable experts and suppliers willing to help this secret project.[5]

Despite the available information, much about the performance of Khan's centrifuge program remains uncertain. How many centrifuges were enriching at any given time? How well did the centrifuges enrich over their lifetime? How much WGU was considered to be enough for Pakistan's purposes? Have there been other needs for enriched uranium that have reduced the amount dedicated to weapons?

With these uncertainties, this assessment recreates scenarios of the installation and operation of gas centrifuges in Pakistan. It uses these scenarios to estimate the stock of WGU as of the end of 2014.

In its early days, which include much of the 1980s, the centrifuge program was deeply plagued by technical problems. In the early 1980s, according to a knowledgeable European centrifuge expert long familiar with Pakistan's centrifuge program, Pakistan deployed almost 1,000 P1 centrifuges in six cascades. After three months, about 30 percent had failed. At the end of six months, almost all had failed and the cascades were stopped. After this date, Pakistan built additional P1 cascades and operated them more successfully. It also focused on producing the P2 centrifuge, a stolen German design which is more efficient and powerful. Khan and his colleagues realized that the P1 centrifuge would never be reliable and the P2 centrifuge was more promising, albeit significantly harder to build.

In this estimate, Pakistan is assumed to have deployed about 3,000 P1 centrifuges by 1985 and then gradually replaced them with P2 centrifuges on a one-cascade-to-one cascade basis from 1985 to about 1992. The switch in centrifuge type was eased considerably, because Pakistan could use its existing cascade piping and instrumentation. The Urenco cascade designs Khan acquired in the 1970s allowed for the placement of either the Dutch or German centrifuge in a specific cascade position, after some minor adjustments. Post-1991, Pakistan is assessed to have increased its numbers of P2 centrifuges.

[5] *Peddling Peril*, op. cit. See particularly early chapters which included information from the 1970s Dutch government investigation of Khan's activities while in the Netherlands.

Included in information seized by national investigators of the Khan network is a confidential KRL video with footage of P2 centrifuge cascades in a large cascade hall at KRL that was filmed around 2000. To give Libya a preview of the centrifuge facility that it had purchased from the Khan network, Khan provided Libyan officials this video that featured the facilities at KRL, including the cascade hall and associated centrifuge development and manufacturing facilities. An IAEA expert estimated that the large cascade hall held about 8,000-10,000 P2 centrifuges.[6] Based on analyzing the cascade piping, he assessed that these centrifuges were in cascades dedicated to making only low enriched uranium, such as 4 percent low enriched uranium (LEU). Other cascades located at KRL or Gadwal would take the low enriched uranium up to weapon-grade.

The video does not indicate if there were other similarly sized cascade halls holding P2 centrifuges producing LEU as the first step in making WGU. It is possible that the hall had a twin in a nearby KRL building, and this possibility is discussed below.

KRL developed a method to produce weapon-grade uranium in four steps. This method is illustrated in a drawing of a centrifuge plant, believed to be for the one Libya purchased from the Khan network and discovered during the Khan investigations. It shows a complex of buildings, with one building containing all the centrifuges. Inside it are several halls. Two such halls flank a central area holding inverters for powering the centrifuges and other equipment for feeding in the uranium and extracting the enriched and depleted uranium. Each of these two halls held 15 cascades, each with 164 centrifuges, dedicated to producing about 3.5-4 percent LEU, with a total in both halls of 4,920 centrifuges. Another hall in the factory held three groups of cascades, which could take 4 percent LEU to 90 percent in three steps--from about 4 percent to 20 percent, 20 percent to 60 percent, and 60 percent to 90 percent, or weapon-grade. This hall contained a total of 14 cascades, with 1,896 centrifuges. In total, the building contained 6,816 centrifuges.

In the case of Pakistan, the video shows about double the number of centrifuges in the KRL hall devoted to making about 4 percent LEU than in the halls described in the plant drawing. The size of the buildings at KRL, visible in commercial satellite imagery, is more consistent with buildings that would hold only one hall containing 8,000-10,000 P2 centrifuges instead of two such halls.

It is possible that in 2000 there was more than one building at KRL containing 8,000-10,000 P2 centrifuges devoted to making 4 percent enriched uranium. However, in this estimate it is assumed that KRL had only one such hall involved in the first step of making weapon-grade uranium. Needless to say, this issue remains an uncertainty in the analysis.

Other information supplied by the Khan network to its Libyan customer gives an indication of the enrichment output of a P2 centrifuge plant enriching in four steps. In this case, a document describes a centrifuge plant holding 5,832 P2 machines that would be able to make about 100 kilograms of weapon-grade uranium per year.[7] In this case, about two-thirds of the centrifuges would make 4 percent LEU, and the other one-third would be organized into three steps to enrich from 3.5 percent LEU to weapon-grade uranium. These specifications, combined with the fact that a P2 centrifuge has an enrichment output of about 5 separative work units (swu) per year, imply that the production of each kilogram of weapon-grade uranium requires 292 swu, rounded to 300 swu (300 swu per kilogram of WGU). This value is considerably larger than the value when the

[6] *Peddling Peril*, op. cit., p. 129.
[7] *Peddling Peril*, op. cit., p. 123.

cascades are ideal. In the ideal case, the values are about 180-190 swu per kilogram of WGU, assuming a tails assay of 0.3-0.35 percent.[8] In practice, however, a value of about 300 swu per kilogram may be too low for the Pakistani four step cascade designs.

A 1995 table of WGU production prepared and signed by the Pakistani Ashraf Ali in March 1995, and seized by Swiss authorities during investigations of members of the Khan network, gives flow rates through the four steps: 50 tonnes of natural uranium per year to produce of 96 kilograms of WGU per year.[9] Assuming that the tails assay in the first step is 0.35 percent, the estimated amount of separative work per year, via a comparison to an ideal cascade calculation, is about 380 swu per kilogram of WGU.

To make WGU, Pakistan would need additional centrifuges at KRL or Gadwal to enrich from 3-5-4 percent to 90 percent. Assuming that about two thirds of the total number of centrifuges are in the first step, and another one third are in the other steps. Thus, Pakistan would need an additional 2,600 to 3,300 centrifuges to make the WGU in steps 2, 3, and 4.

In sum, at the time when the video was made or approximately 2000, the total number of centrifuges dedicated to making WGU is estimated as 8,000-10,000 centrifuges in a main hall making 3.5-4 percent LEU, combined with another 2,600-3,300 centrifuges located elsewhere, for a total of about 10,600-13,300. Each kilogram of WGU is assessed to require nominally about 300-380 swu. With each P2 centrifuge having an output of 5 swu per year, the total enrichment capacity was 53,000-66,500 swu per year. Ignoring other inefficiencies which will be included below in estimating the WGU stock at the end of 2014, that enrichment output is sufficient to produce about 140-220 kilograms of weapon-grade uranium per year.

In the video, one can also see centrifuge test stands that involve centrifuges significantly longer than the P2 centrifuge. Khan also stole parts of the designs of the German G4 design that is double in length (and enrichment output) of the P2 centrifuge. Khan has called it the P3 centrifuge. Pakistan may have deployed a P3 centrifuge starting in the late 2000's. This estimate assumes a gradual buildup in the numbers of the P3 centrifuge during that time period.

Pakistan may be working on deploying an even longer, more advanced centrifuge, which is sometimes called the P4 centrifuge. Some of the centrifuges being tested in the promotional video appear longer than the P3 centrifuge. However, Pakistan is assumed in this estimate not to have deployed a P4 centrifuge as of the end of 2014. Likewise, based on procurement data and interviews with knowledgeable officials, Pakistan is unlikely to have deployed large numbers of centrifuges with carbon fiber rotors that would spin much faster and thus achieve a significantly greater enrichment output than the P2 or P3 centrifuge, which has maraging steel rotors.

Key Phases of the Centrifuge Program

More specifically, the estimate includes four key historical phases:

[8] The tails assay could be greater but here it is assumed to be about 0.3-0.35 percent because historically Pakistan has suffered from a shortage of uranium that would tend to encourage lower average tails assays over time. On the other hand, the tails assay could by 0.2-0.25 percent but based on the information from a long-time, close follower of Pakistan's centrifuge program, the tails assay historically tended toward 0.3 percent tails.

[9] This Ashraf Ali could be the same as mentioned in a recent article by Khan, see A. Q. Khan, "Unsung Heroes," *International*, *The News*, September 22, 2014. https://www.thenews.com.pk/Todays-News-9-274235-Unsung-heroes

- **Up to 1991**. The number of centrifuges reach 3,000 P1 centrifuges in 1985. They are then replaced by P2 centrifuges, a process finished by 1991. At the end of this phase, there are no longer any P1 centrifuges but there are 3,000 P2 centrifuges. In addition, in the early 1980s, Pakistan received 50 kilograms of weapon-grade uranium from China;
- **From 1991 to 1998**. During this period, Pakistan reportedly did not produce WGU, although it is widely believed to have produced LEU, taken as 20 percent enriched.[10] In addition, the numbers of P2 centrifuges increased to about 8,000 in 1998;
- **From 1998 to2005**. Pakistan concentrated on making WGU during this period. It is assumed that it enriched its stocks of LEU to WGU, getting a significant boost in its WGU stock albeit over time. It increased the number of enriching P2 centrifuges to 11,000-14,000 P2 centrifuges by 2002 and 11,000-15,000 P2 centrifuges during 2003-2005; and
- **Starting in 2006**. Pakistan gradually deployed P3 centrifuges that replaced aged P2 centrifuges without increasing the number of P2 centrifuges. As P3 centrifuges are deployed, old P2 centrifuges in equal number are withdrawn from service. By 2014, 3,000 P3 centrifuges are assumed to have been deployed.

In estimates of WGU production, a number of assessments are applied to the predicted operation of the P1, P2, and P3 centrifuges, namely:

- The separative power of the P1 centrifuge is taken as having a single machine enrichment output of about 1.5 separative work units (swu) per year; the P2 centrifuge is taken as 5 swu per year; and the P3 centrifuge is estimated to initially have an output of 7 swu per year and increase to 10 swu per year in 4 years. The lifetime of Pakistan's centrifuges is about ten years.[11]
- The production of WGU progresses in four steps from natural to weapon-grade uranium, where the tails of the first step is 0.3-0.35 percent. Pakistan's centrifuge cascades are inefficient compared to an ideal cascade, which means that the average individual centrifuge separative power is less when in cascade than when running individually. The amount of WGU produced as a function of the plant's total separative work is less than predicted by formulas for ideal cascades. As discussed above, Khan told his customers in essence that the production of each kilogram of WGU would require 300-380 swu; and
- The centrifuge cascades encountered additional inefficiencies while producing WGU. These include high rates of centrifuge breakage during routine operation and extraordinary events such as earthquakes, and the interrupted operation of the cascades, for example, due to excessive vibration of the centrifuges. These additional inefficiencies are difficult to predict but are estimated to reduce production of separative work by 10 to 20 percent.

In each period, an estimate is first made of the type and number of centrifuges, based on the above bullets. This method leads to a range of initial total separative work for each phase. Afterwards, the inefficiency factor discussed above (3rd bullet) is applied to this separative work estimate. The amount of WGU produced is derived by applying a range of 300-380 swu per kilogram of WGU.

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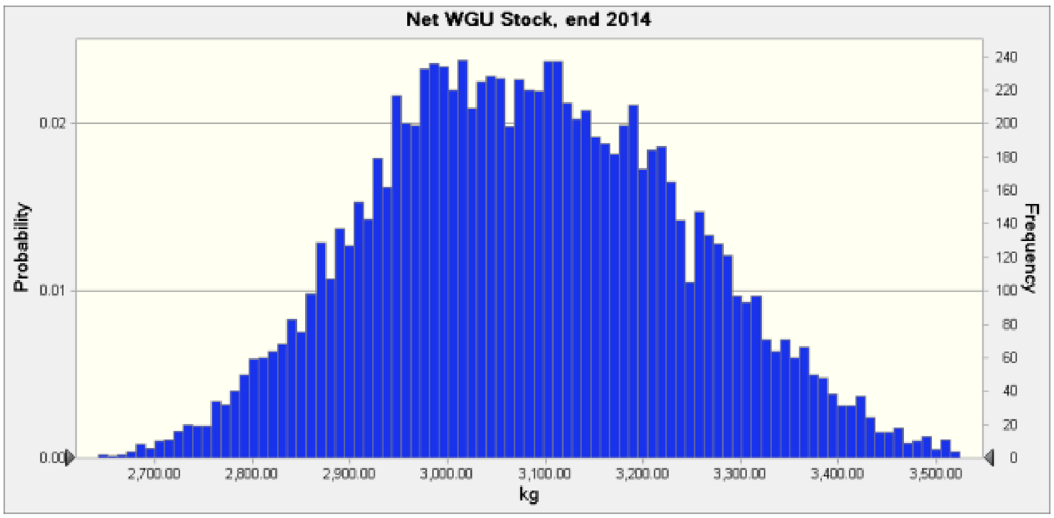
[10] Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996* (Oxford: Oxford University Press, 1997), p. 277-9.
[11] See for example, A. Q. Khan, "Unsung Heroes," op. cit.

The amount of WGU used in the 1998 tests is subtracted from the total. About 90-120 kilograms of WGU are estimated to have been used in six nuclear tests. Another drawdown of 2-4 percent of the total WGU stock results from processing losses during the production of the WGU and its conversion into weapon components.

The calculations are done using Crystal Ball™ software. The estimated total amount of WGU has a median of 3,080 kg with a standard deviation of 155 kilograms and a full range of 2,620 to 3,635 kilograms. The standard deviation measures how many results are within almost 70 percent of the median. It can be used to produce a range of values that likely captures the true value. Here, the range is defined somewhat more broadly, as capturing at least 80 percent of all the values. In this case, the range is 2,880-3,290 kilograms of WGU, where all of these values are within 210 kilograms of the median. Here, with a distribution that is not symmetrical about the median, or a skewed distribution, a value of 210 is necessary to include the upper bound of 3,290 kilograms.



The results of each period follow, where again the distributions are skewed.

Table Total WGU by Time Period

	Median WGU(kg)	**Range (~80% of values) (kg)**
Through 1991:	125	110-140 (+15 captures all values)
From China	50	
1991-1998 (post-1998)	435	375-510 (+75 captures all values)
1999-2005	975	880-1085 (+110 captures all values)
2005-2014	1670	1510-1850 (+180 captures all values)
Subtotal**:**	**3,255**	
Withdrawals, Losses	-185	
Total	**3,070**[12]	**(rounded, median is 3,080))**

[12] Rounding of the individual values accounts for the small difference of about 10 kilograms between the median of the final distribution of the WGU stock and the result of adding separately the means of each distribution of WGU production for different periods.

A boost in the production of WGU occurred in the period after the 1998 nuclear tests, mainly because stockpiled LEU allowed more rapid production of weapon-grade uranium. Pakistan is likely to have done this enrichment over an extended period of time. It could have added cascades to take the 20 percent material to weapon-grade in two steps. Alternatively, it could have used the extra 20 percent material to increase the feeding rate into the third and fourth steps, increasing the output of weapon-grade uranium from the final step.

Most of the WGU in this estimate was made in the fourth period, 2005-2014, when the program was at its peak and was most experienced. This period is also the longest of the four periods.

There have been questions about whether a major 2005 earthquake severely damaged the Kahuta enrichment plant. An analysis by ISIS at the time did not find any structural damage in the buildings supporting widespread centrifuge destruction.[13] Based on Khan network information, Pakistan had installed specially-designed shock absorbent pads under its centrifuges to increase the chances that they would withstand earthquake damage.[14] Nonetheless, this and other earthquakes are believed to have destroyed centrifuges, even if the building did not show structural damage.

If Pakistan is still making WGU as described in this estimate, at the end of 2014 Pakistan had an estimated enrichment output dedicated to WGU production of almost 100,000 swu per year. With that output and the inclusion of inefficiencies, it could produce about 215 kilograms of WGU per year, with a range of 190-240 kilograms per year.[15] Over the roughly 30 years the program has made WGU, it has produced an average of about 100 kilograms of WGU per year.

The predicted WGU stock is large. A key question is whether at some poing Pakistan decided to end further production of WGU for nuclear weapons due to a lack of need, as happened in other military nuclear programs. Such a cutoff could have happened in the last period as Pakistan was ramping up plutonium production. However, Pakistan has not made any statements implying such a step. Moreover, this period witnessed dramatic buildups in India's nuclear weapons capabilities, which Pakistan viewed with alarm. Thus, absent evidence of cutbacks in WGU production, this estimate assumes WGU production continued, but this issue remains an uncertainty in the analysis.

There are two uncertainties affecting this analysis that deserve attention, one mentioned earlier and a new one. The first is whether this approach accurately captures Pakistan's enrichment output dedicated to making weapon-grade uranium for nuclear weapons. For example, Pakistan may have more centrifuges than estimated here. There have also been reports that Pakistan has built an additional centrifuge plant or building.

Another uncertainty is whether some fraction of this enrichment capacity has been used for other purposes. Pakistan has no civilian need for HEU. However, according to an unconfirmed media

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[13] "Kahuta Enrichment Plant Escapes Earthquake Damage, Pakistani Official Declares," *WMD Insights*, Issue 1 Dec 2005/Jan 2006.

[14] For a discussion of the impacts of earthquake on Kahuta in the 1980s and the countermeasures taken to limit damage, see See also Feroz Hassan Khan, *Eating Grass: The Making of the Pakistani Bomb* (Stanford: Stanford University Press, 2012).

[15] This value is calculated using the median and the range including 80 percent of the full range of the WGU distribution for the years 2006 through 2014. It should be noted that the inefficiencies reduce the annual WGU estimate significantly.

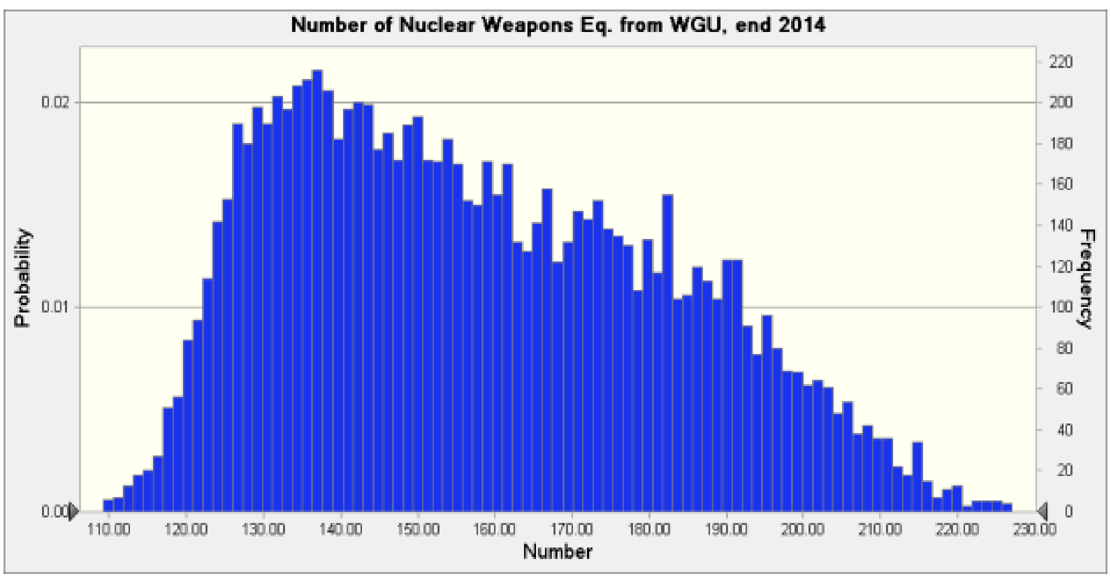
report, Pakistan has launched a naval reactor program.[16] That program while likely in its infancy is reported to involve a land-based prototype reactor that undoubtedly uses enriched uranium fuel.[17] Enriched uranium is used to reduce the size of the reactor core so that it will better fit in the tight confines of a submarine. If the reactor is similar to the Indian land-based prototype reactor, it would require roughly 10,000 swu to make a core load of fuel.

Nuclear Weapons Equivalent

It is assumed that most of Pakistan's nuclear weapons use WGU. It could use the WGU to fashion fission weapons. It could use WGU in conjunction with plutonium, or a "composite core," to seek fission weapons with a significantly greater explosive yield. It could also use the WGU with plutonium in designing one-stage thermonuclear explosive devices, which combine thermonuclear material with plutonium and weapon-grade uranium in a core.

If the WGU were used in fission weapons without any plutonium, then Pakistan would likely need less than a significant quantity of WGU. How much less is unclear, but 15-25 kilograms per weapon would likely include many possible weapons designs. Over time, Pakistan has likely learned to use less WGU per weapon of a fixed explosive yield.

Crystal Ball™ is used to estimate the nuclear weapon equivalents of the WGU stock. The median of this distribution (shown below) is 155 weapons equivalent, with a standard deviation of 25 weapons and a full range of 109 to 236. About 80 percent of the values of this skewed distribution are in the range of 125-195. All of these values are within about 40 of the median, where the value of 40 is necessitated by the upper bound.



[16]Andrew Detsch, "Pakistan's Oversized Submarine Ambitions, *The Diplomat*, October 09, 2013, citing Haris Khan, a senior analyst at PakDef Military Consortium, an independent Tampa-based think tank. According to Khan, since 2001 the Pakistan Atomic Energy Commission (PAEC) has been working on KPC-3, a project "to design and manufacture a miniaturized nuclear power plant for a submarine." http://thediplomat.com/2013/10/pakistans-oversized-submarine-ambitions/

[17] Ibid.

The actual number of nuclear weapons Pakistan built from its stocks of WGU is unknown. With requirements for WGU in the weapons production pipeline and in reserves, it is reasonable to assume that only about 70 percent of the estimated stock of weapon-grade uranium is in nuclear weapons. Thus, the predicted number of weapons made from WGU at the end of 2014 is about 110. The range is about 85-135 weapons.

Weapon-Grade Plutonium Production

Pakistan has also accumulated a stock of separated plutonium for nuclear weapons and is finishing the construction of a large plutonium production and separation capability for weapons. Its plutonium stock depends on a set of heavy water moderated reactors at the Khushab nuclear site and a plutonium separation plant near Rawalpindi and perhaps another one either nearing completion or operational at Chashma.

Pakistan started operating the first Khushab reactor in April 1998. Pakistan has never provided information about the power or operational experience of this reactor. Governmental and media reports in the early and mid-1990s provided a range of estimates of the reactor's power, namely 40-70 MWth.[18] In this assessment, the range of 40-60 MWth is used. Plutonium has been separated from this reactor's fuel at the New Labs facility near Rawalpindi.

In the early 2000s, Pakistan embarked on a major expansion at the Khushab site by building three more reactors, called Khushab-2, Khushab-2, and Khushab-4. Pakistan has not officially acknowledged the existence of these four reactors, let alone provided information about their power or operation. ISIS was the first group to reveal publicly the existence of these new reactors by using commercial satellite imagery. It has subsequently tracked their construction progress. Repeated attempts to obtain official information about the reactors have failed. One senior Pakistani official once quipped to the author that Pakistan lets ISIS reveal Pakistan's nuclear weapon production facilities such as the Khushab reactors.

These newer reactors are assessed as having a larger power rating than the original one. How much larger is controversial. Original ISIS assessments were based on the size of the reactor vessel of the second Khushab reactor that was visible inside the reactor building in commercial satellite imagery. This reactor vessel had a diameter considerably larger than the vessel in the first reactor and was judged as being large enough to support a reactor with a much greater power than the first one.[19] However, this assessment was essentially a judgment of the ultimate capability of the reactor, not the power Pakistan would achieve in them, particularly during its first years of operation. Despite concluding that the power is not as great as originally predicted, the assessment remains that the newer reactors have a greater power than the first one.

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[18] See *Plutonium and Highly Enriched Uranium 1996* (p. 279) for a discussion of several of these estimates, which included one reported in 1995 by Mark Hibbs in *Nucleonics Week*, who listed the power as 50-70 MWth. In addition, there were conflicting estimates by the U.S. government and a declassified Russian intelligence report, which were 40 and 70 MWth, respectively.

[19] Albright and Paul Brannan, "Commercial Satellite imagery Suggests Pakistan is Building a Second, Much Larger Plutonium Production Reactor," ISIS Report, July 24, 2006. http://isis-online.org/uploads/isis-reports/documents/newkhushab.pdf

Since that assessment, one important development has been that the forced-air cooling towers of these three new reactors have been built. An evaluation of those cooling towers does support that the newer reactors have a greater power than the first reactor. In this report, ISIS assesses that the power of each of the Khushab-2 and -3 reactors is about 80-120 MWth, or about double that of the first reactor. Based on a comparison of cooling towers among the reactors, the power of Khushab-4 may have a greater power than the second and third reactors.

In the last several years, the three new reactors appear to have started:

- Khushab-2 started operating by early 2009;[20]
- Khushab-3 started by late 2012;[21] and
- Khushab-4 apparently starting in late 2014 or early 2015.[22]

Faced with a lack of specific operational or reactor design data, this estimate uses a single equation to estimate total plutonium production in a reactor:

Total Plutonium (kgs) = P (Reactor Power) x C (Capacity Factor) x D (Days in Operation) x PF (Plutonium Conversion Factor) x 0.001,

where the plutonium conversion factor (PF) serves to convert the amount of energy produced by the reactor into the amount of weapon-grade plutonium in the discharged fuel (in units of grams of weapon-grade plutonium per energy produced, g/MWth-d). For the production of weapon-grade plutonium in the Khushab reactors, values of about 0.95-0.97 g/MWth-d are used.[23] The last factor on the right hand side of the equation converts the mass from grams to kilograms.

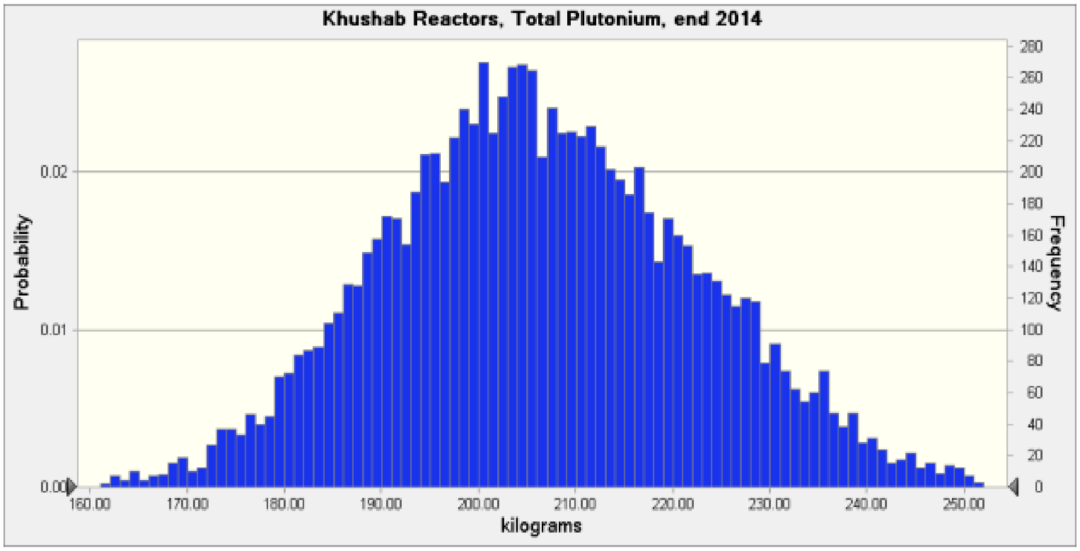
The reactors' power is given above, where a range is used in the calculation. The range is assumed to have a normal distribution with the mean at the midpoint of each power range. This makes the mid-point most likely. There is no information about the reactors' capacity factor but each reactor is believed to have a relatively low average capacity factor of about 40-50 percent.

The plutonium has few other uses than nuclear weapons. The only drawdown included in this estimate involves processing losses, which are taken as ranging from 2-4 percent of the total plutonium produced. The losses could occur in the plutonium separation plant or in the facility making plutonium weapons components.

The calculation of plutonium produced in these reactors is also performed with Crystal Ball® software. Below is the distribution of net plutonium values, reflecting the relatively small drawdowns. The median is about 205 kilograms with a standard deviation of 16.3 kilograms and a

[20] Paul Brannan, "Steam Emitted from Second Khushab Reactor Cooling Towers: Pakistan May be Operating the Second Reactor," ISIS Report, March 24, 2010.
[21] Zia Mian, "Pakistan Begins Operating Third Khushab Plutonium Production Reactor," *IPFM Blog*, June 30, 2014. http://fissilematerials.org/blog/2014/Pakistan_begins_operating.html
[22] Albright and Serena Kelleher-Vergantini, "Pakistan's Fourth Reactor at Khushab Now Appears Operational," ISIS Report, January 16, 2015, http://isis-online.org/isis-reports/detail/pakistans-fourth-reactor-at-khushab-now-appears-operational/.
[23] International Panel on Fissile Materials, *Global Fissile Material Report 2010, Balancing the Books: Production and Stocks*, 2010.

full range of 150 to 270 kilograms.[24] More than 80 percent of the values are within the range of 185 to 230 kilograms. The values in this range are within 25 kilograms of the median.



About 60 percent of the plutonium has been produced in the Khushab-1 reactor, reflecting that the new reactors have not operated until relatively recently. Most of the plutonium has likely been separated and is usable in nuclear weapons.

Annual plutonium production has been increasing in recent years as the new reactors have come on-line. When all four reactors are operating at their nominal powers, plutonium production will reach about 70 kilograms per year (central estimate), implying a large capability to make nuclear weapons.

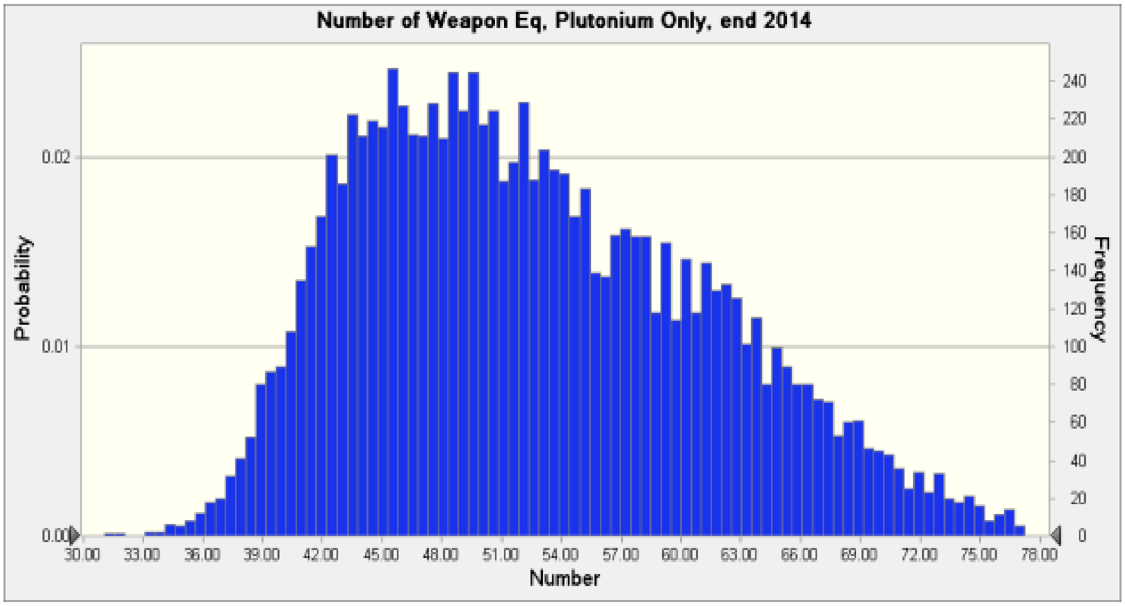
Nuclear Weapons

Pakistan apparently uses plutonium to further miniaturize its nuclear weapons for deployment on short-range missiles and submarine launched missiles. The methods it uses to accomplish that goal are unknown, although Western intelligence stated that Pakistan had learned to apply levitation principles to its nuclear weapon designs prior to the 1998 nuclear tests.[25] It undoubtedly benefited from its six underground tests in 1998.

In this study, a Pakistani plutonium-based weapon is assumed to contain between three and five kilograms of plutonium. Although five kilograms are rather large, this figure is viewed as an upper bound. A weapon could use this amount of plutonium in order to increase its explosive yield or permit further miniaturization. With little information about Pakistani nuclear weapons, all values in the range are viewed as equally likely. The resulting calculation using Crystal Ball™ software results in a skewed distribution with a median of about 51 nuclear weapons equivalent (rounded in table below to 50). The distribution's standard deviation is almost 9 and full-range is

[24] In the case where the range for the reactors' power were assumed to be a uniform distribution (e.g. each value is equally likely), the median is 215 kilograms and the full range is 154 to 297 kilograms. In essence, the upper bound is increased and the median increases by 10 kilograms.
[25] *Peddling Peril*, op. cit.

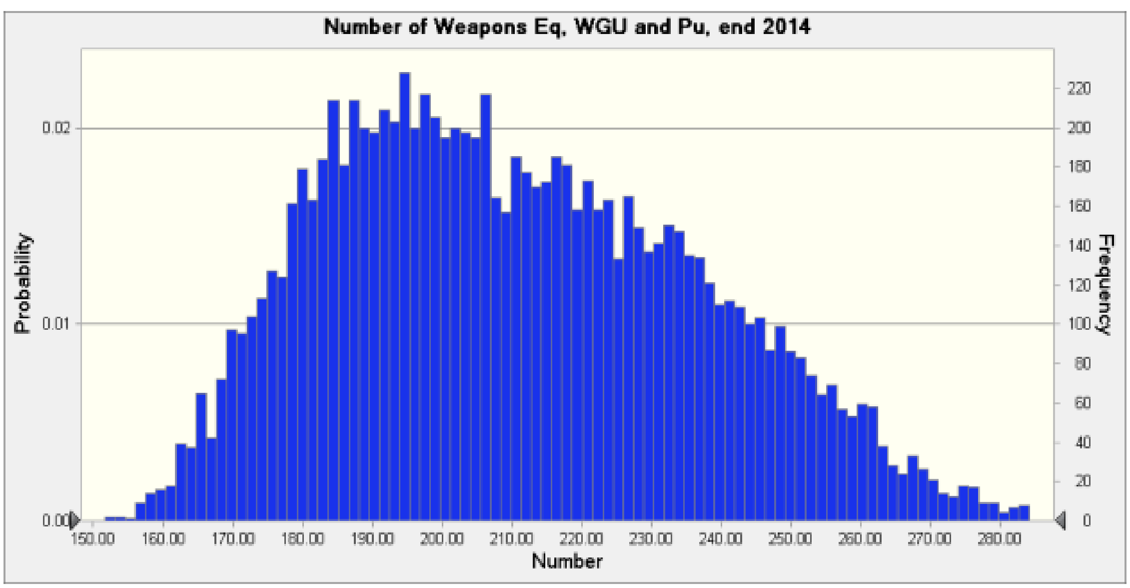
30-85 weapons equivalent. Over 80 percent of the values are in the range of 42-65. All the values in this range are within 14 of the median.



Using the estimate that about 70 percent of the plutonium is in nuclear weapons, Pakistan would have about 35 plutonium-based nuclear weapons, or a range of 30-45 of them.

Nuclear Arsenal with WGU and Plutonium

As mentioned above, nuclear weapons can be made from either plutonium or WGU or both combined. To give an indication of the total potential number of nuclear weapons' equivalent, the number of WGU- and plutonium-based nuclear weapons are added independently. The resulting distribution has a median of 208 nuclear weapons and a standard deviation of 26. The full range is roughly 150-305 weapons. Over 80 percent of the values are in the range of about 180 to 245. In this case, these values are within 40 of the median. The skewed distribution follows:



Assuming that 70 percent of the fissile material is in nuclear weapons, the predicted number of weapons is about 145 nuclear weapons, with a range of 125 to 170 weapons.

Summary

The estimates are summarized in the following two tables, where values are rounded.

	Pakistan's Military Fissile Material Stocks, end of 2014 (kg)	
	Median	**Range**
Plutonium	205	185-230
Weapon Grade Uranium	3,080	2,880-3,290

Table Estimated Number of Nuclear Weapons, Equivalent and Built through 2014		
	Nuclear Weapons Equivalent	**Nuclear Weapons Built**
Plutonium Only	50 (median)	35(median)
WGU Only	155 (median)	110 (median)
Total	205 (range: 180-245)	145 (range: 125-170)

Last Word

Few believe Pakistan will sign the Nuclear Non-Proliferation Treaty (NPT) or agree unilaterally to abandon its nuclear weapons as part of a South Asian nuclear weapons free zone. It has not signed the Comprehensive Test Ban Treaty (CTBT), but it has announced that it will not be the first to test again in the region, implying it would test again only if India does. In addition, Pakistan has for many years blocked the start of Fissile Material Cutoff Treaty (FMCT) negotiations at the Conference on Disarmament in Geneva, which operates by consensus. Pakistan believes it needs a larger nuclear arsenal and thus must produce more fissile material to build that larger arsenal. With no constraints on its fissile material production for weapons, Pakistan, like India, appears to be greatly expanding its stocks of nuclear explosive materials and nuclear weapons. Finding ways to limit these stocks of materials and weapons should be a priority.