What is the Size of Khushab II?

By

Thomas B. Cochran, Ph.D.
Director, Nuclear Program
Natural Resources Defense Council, Inc.

September 8, 2006

Natural Resources Defense Council, Inc.
1200 New York Avenue, N.W., Suite 400
Washington, D.C. 20005
Tele: 202-289-6868
tcochran@nrdc.org

Executive Summary

The Bush administration and an independent security organization are at odds over the size and potential threat posed by a new nuclear reactor Pakistan is constructing to produce plutonium for weapons. Our analysis indicates that the reactor capacity is consistent with the administration's calculation, which is substantially smaller than what the independent analysts estimate. The reactor's output, however, still could significantly increase Pakistan's ability to produce nuclear weapons.

In late July, the Institute for Science and International Security ("ISIS") released a report indicating that Pakistan is building a new large heavy-water reactor to produce plutonium, which would significantly expand that country's nuclear weapons capabilities.[1] Based on satellite images, ISIS's report estimates that Pakistan's new production reactor under construction at Khushab ("Khushab II") would be capable of operating at a power level in excess of 1,000 megawatts-thermal ("MWt").

According to the New York Times, federal officials maintain that the reactor under construction is approximately the same size as a smaller reactor Pakistan now uses to make plutonium for its nuclear program, and that it may be a replacement for it.[2] A U.S. State Department spokesman said that "the [new] reactor will be over 10 times less capable" than what ISIS estimates.[3]

ISIS has estimated, we believe erroneously, that the Khushab II reactor vessel is approximately 5 meters (m) in diameter. Since the heavy-water production reactors at the U.S. Savannah River Site have steel reactor vessels that are 16.25 ft (5 m) (P, K and L reactors) and 18.5 ft (5.6 m) (C reactor) in diameter, ISIS assumed that the Khushab power level would be comparable to a Savannah River reactor's operation power.

The ISIS estimate is based on the following assumptions:

1) the size of the reactor building is a poor indicator of the reactor's power;
2) a better indicator is the size of the reactor vessel; and
3) the size of the reactor vessel can be estimated from commercial satellite imagery.

We agree with assumptions 1 and 2, but disagree with assumption 3. ISIS analysts David Albright and Paul Brannan likely mistakenly assumed that the size of a dark ring in the reactor building under construction – as seen in DigitalGlobe's Quickbird satellite image and measured to be about 5 m in the 0.7 m resolution image – is the size of the reactor vessel. As we argue in this report, the actual size of the reactor vessel is smaller and will fit inside the ring, and thus the power level is more likely to be in the 40 to 100 MWt range, rather than 1,000 MWt or larger.

---

[1] http://www.isis-online.org/publications/southasia/newkhushab.pdf

[2] William J. Broad and David E. Sanger, "U.S. Disputes Report on New Pakistan Reactor," New York Times, Aug. 3, 2006, p. 6.

[3] Shahzeb Jillani, "Pakistan nuclear report disputed," BBC News, Aug. 7, 2006.

Assuming Pakistan continues to operate Khushab I, the addition of Khushab II would allow Pakistan to increase its rate of plutonium production for weapons by a factor of two to three. If Pakistan modifies its weapon designs as the United States did more than 50 years ago, it could further increase its weapon output by an additional 60 percent or more. Thus, while we believe Pakistan's weapon production capacity would be considerably less than what ISIS projects, it nevertheless would be a significant increase.

The Reactor Vessel

Let us begin by examining the configuration of two early heavy water reactors designs: the Canadian National Research Experiment ("NRX"), a 42 MWt heavy water research reactor that achieved criticality in 22 July1947, and the Canada-India Reactor ("CIRUS"), a 40 MWt Canadian supplied heavy water reactor based on the NRX design that achieved criticality on July 10 1960.[4] The plutonium used in India's first nuclear test in 1974 was produced in CIRUS, thus making CIRUS India's first production reactor.

The following two figures, show the vertical (see p. 4) and horizontal (see p. 5) cross sections of the NRX reactor.[5] From these figures we estimate that the inner diameter of the concrete biological shield is about 5.3 m. Within this circular shielding is the 8.75 ft (2.7 m) diameter reactor vessel, called a calandria, surrounded by a thick graphite neutron reflector and what appears to be a thin steel liner.

With respect to CIRUS, according to Atomic Energy of Canada, Ltd. ("AECL"): [6]

> The reactor proper, shown in Figure I-6 [not reproduced here but similar to NRX shown at p. 4], is carried on a heavy steel frame consisting of a machined assembly of welded plates and shapes supported on four heavy steel columns. The main floor plate of the reactor, 5 inches thick and 18 feet 0 inch [5.486 m] in diameter, is carried on this frame and supports in turn the lower thermal shields, the calandria, and the graphite reflector. The floor plate also supports the cast iron side thermal shields and the peripheral ducts through which cooling air is supplied to and removed from the reactor.

As seen from "FIG. 1" on p. 6, the outer diameter of the thin aluminum calandria is 2.756 m, and the outer diameter of the graphite reflector is 4.584 m.[7] These dimensions are essentially the same as those of the NRX reactor components, which is not surprising since CIRUS is based on the NRX design. AECL also notes:[8]

To arrest radiations escaping from the reactor, two concentric rings of cast iron are provided, each 6 inches thick. They are separated from each other and from the graphite by 2-inch annular gaps. These shields are air cooled and openings are provided in them to accommodate the thermal columns.

---

[4] The "US" in "CIRUS" referred to the fact that the heavy water for the reactor was supplied by the United States.

[5] Reproduced from D.G. Hurst and A.G. Ward, "Canadian Research Reactors."

[6] Atomic Energy of Canada Limited, "The Canada-India Reactor", AECL-1443, Chalk River, Ontario, 1960, p. I-18.

[7] Ibid., Figure 1 following p. II-34.

[8] Ibid., p. I-21.

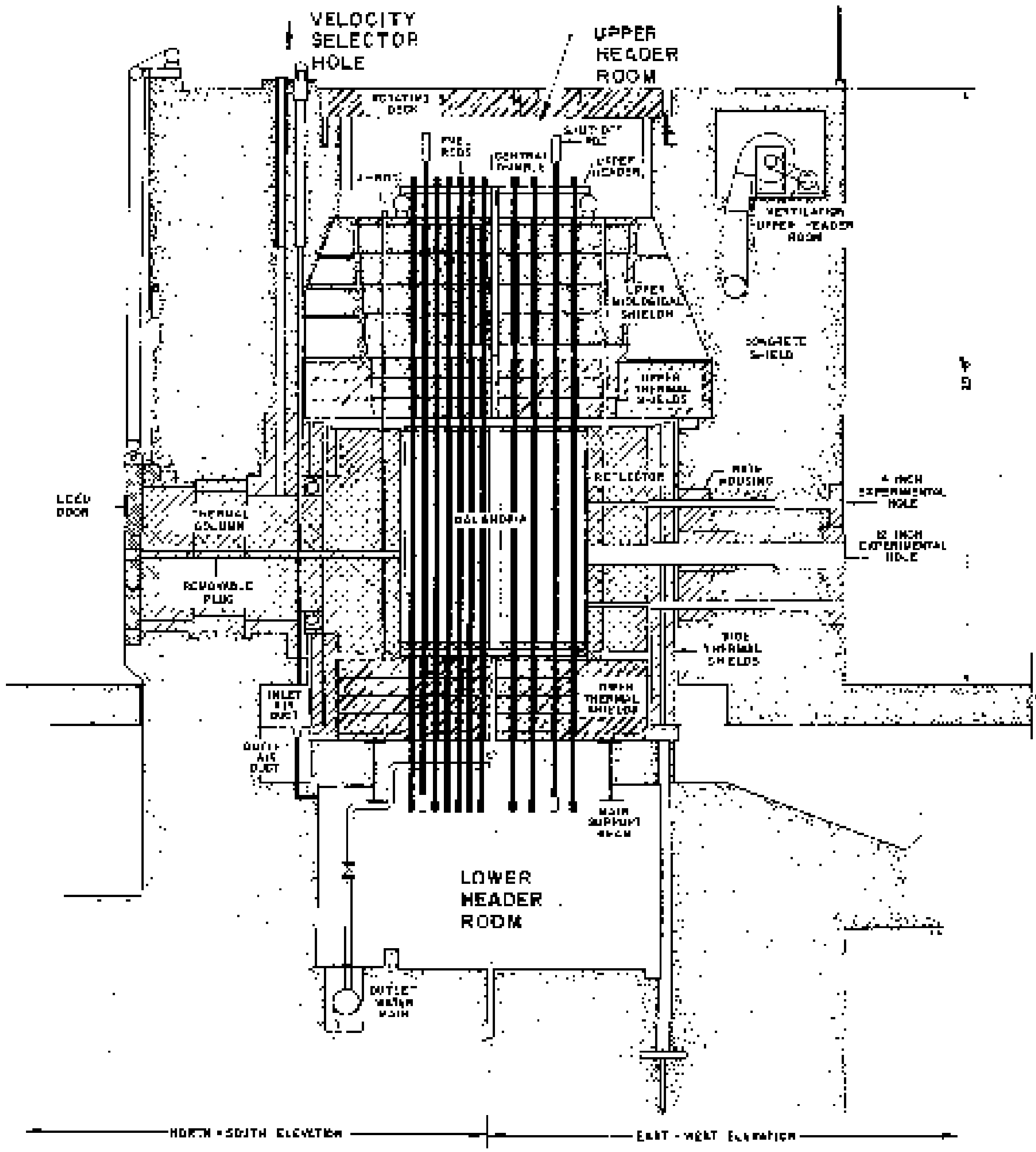


Figure 1-2

Elevation Cross-Section of the NRX Reactor

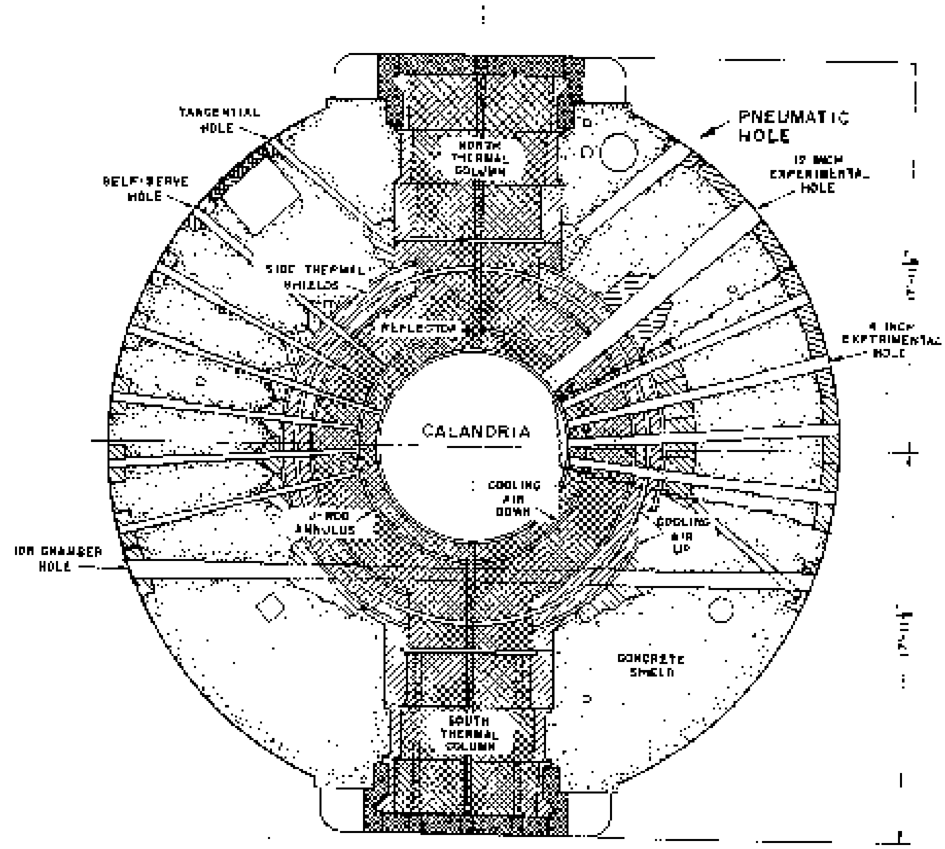
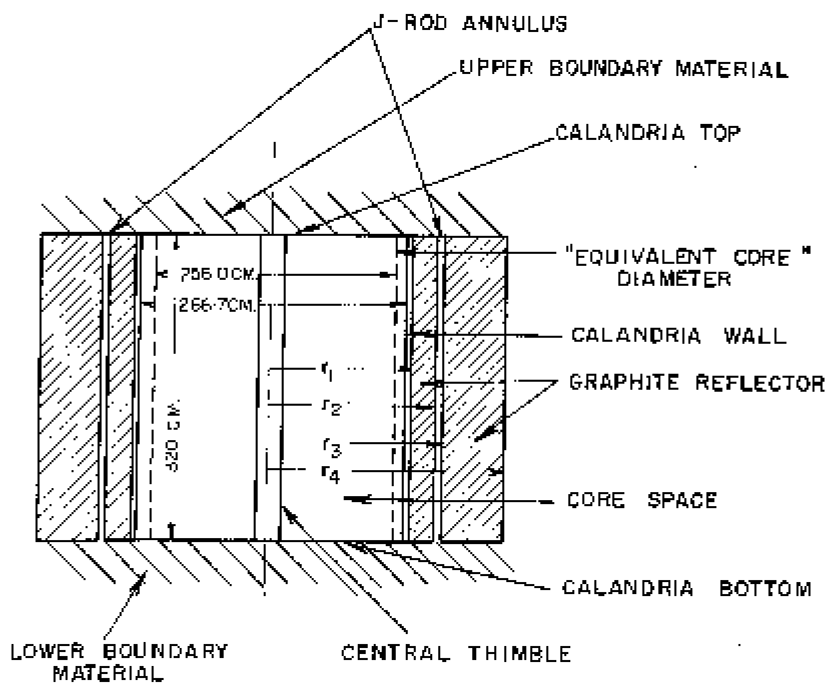


Figure 7-1

Plan Cross Section Through the Reactor Structure

FIG. I

A PHYSICIST'S VIEW OF CIR



r_1 =	INNER	RADIUS	OF INNER	GRAPHITE	REFLECTOR	= 137·8 CM.
r_2 =	OUTER	"	"	"	"	= 160·7 CM.
r_3 =	INNER	"	" OUTER	"	"	= 167·0 CM.
r_4 =	OUTER	"	" "	"	"	= 229·2 CM.

CORE SPACE CONTAINS

192 NORMAL CALANDRIA TUBES

6 LARGE CALANDRIA TUBES (4")

Thus, the inner and outer diameters of these iron rings are about 4.7 m and 5.4 m, respectively. Within the uncertainty of estimating dimensions from the Quickbird satellite image, the dimensions of these rings are approximately the same those seen at Khushab II.

Thus, one must be careful in extrapolating measurements from satellite images and then making assumptions about them. As we see in the NRX and CIRUS examples the dark ring within the Khushab II reactor building is more likely to be a large space within which the reactor vessel will be placed that may also allow space for a neutron reflector and additional thermal an/or biological shielding. If our analysis is correct then the size of the reactor vessel is much less than five meters and the reactor power will not approach 1,000 MWt.

ISIS believes that we have misinterpreted the function of the round metal object in the Quickbird satellite image and sticks by its claim that it is a reactor vessel. ISIS provides two arguments to support its position:

> a. The NRX and CIRUS reactors are old designs from the 1945-1960 period, even predating Khushab I. To use such a design for a new reactor would be a step backwards.
>
> b. ISIS consulted an expert with knowledge of how heavy water reactors are built and operated. He stated that the reactor vessel is constructed first and then outer shielding is added afterwards, thus expanding the size of the complex. ISIS argues that construction is incomplete and that the 5 m circular object is the reactor vessel and will eventually be surrounded by a larger structure.

We agree that NRX and CIRUS are old designs, and we do not suggest that this is the design of the Khushab II reactor. We only use them as examples to show that the rings seen in the satellite image are not necessarily the reactor vessel.

We disagree with the expert consulted by ISIS. Here we note that it would have been impossible to install the NRX calandria before pouring at least the base of the concrete shield. The calandria sits on thick steel plates that serve as the lower thermal shield. These plates sit on main support beams tied into a concrete structure that has a diameter of about 17 ft 4 in (5.3 m)—which is significantly larger than the 8.75 ft (2.7 m) diameter calandria. Similarly, the 5.486 m floor plate would have to have been installed before the CIRUS calandria.

We turn next to the 100 MWt DHRUVA reactor, India's second heavy water production reactor, whose design and construction has been described by India's Department of Atomic Energy.[9] The excerpt from *Nuclear India*, reproduced below (p. 9), describes how the calandria for India's 100 MWt DHRUVA reactor was not assembled first at the reactor site (as would be argued by ISIS), but was fabricated at the Central Workshops of the Bhabha Atomic Research Centre ("BARC") where it could be precision machined.[10]

The calandria was fabricated from extra low carbon stainless steel plates ranging in thickness from 1.9 centimeters (cm) to 6.5 cm. The main shell of the calandria is 302 cm long has a 372 cm internal diameter.[11] Elsewhere in the same article the diameter is reported to be approximately 3.75 m.[12] The fuel rods are 305 cm in length. Within the calandria assembly and around the fuel lattice core is a 60 cm thick radial, heavy water, neutron reflector, and there are 32 cm and 30 cm axial reflectors at the bottom and top of the core, respectively. The entire DHRUVA calandria assembly is 6.7 m in height.[13]

This calandria assembly must have been lowered by crane and fitted within the concrete reactor vault with its stainless steel lining shown in the sectional elevation of the reactor building (p. 10). "In order to provide adequate radiation shielding, the reactor vault is filled with ordinary water and surrounded by heavy concrete."[14] From the diagram of the reactor experimental facilities (p. 10), the reactor vault is estimated to be about 6 m in diameter and the concrete shielding about 2.4 m thick. The fact that the DHRUVA reactor vault is larger than the dark rings seen in the satellite images of Khushab II suggests that the Khushab II calandria and power level will be less than that of the DHRUVA.

Also, shown below (p. 11) is a calandria for a CANDU-6 heavy water power reactor in transit to the Qinshan Nuclear Power Station in China. Clearly, the calandrias for these very large heavy water power reactors, which operate at 2,084 MWt (728 MWe gross), are not field erected, but are fabricated off-site. In sum, the calandrias of at least some heavy water reactors that operate between 40 MWt to 2,084 MWt—all of the reactors that we have reviewed here—are factory made and subsequently shipped to the reactor sites for installation.

---

[9] Department of Atomic Energy, "India's Indigenous Reactor DHRUVA," *Nuclear India*, Vol. 23/Nos. 11&12/1985.

[10] "Manufacturing of Components for DHRUVA Reactor," *Nuclear India*, Vol. 23/Nos. 11&12/1985, pp. 12-13.

[11] Ibid., p. 3.

[12] Ibid., p. 12.

[13] Ibid., pp. 3, 4 and 12.

[14] Department of Atomic Energy, "India's Indigenous Reactor DHRUVA," *Nuclear India*, Vol. 23/Nos. 11&12/1985, p. 3.

Manufacture of Components for DHRUVA Reactor

CENTRAL WORKSHOPS of BARC was entrusted with the manufacture of a number of assemblies for DHRUVA reactor. Some of the major assemblies and components called for the development of a number of manufacturing techniques and processes to meet the stringent accuracies and complete the work on time. The assemblies and components successfully manufactured and delivered to project DHRUVA in a record time were: calandria assembly, 152 coolant channel assemblies, 7 shield blocks for wet and dry storage of fuel rods, 500 seal and shield plug assemblies and underwater cutting equipment for cutting spent fuel rods etc.

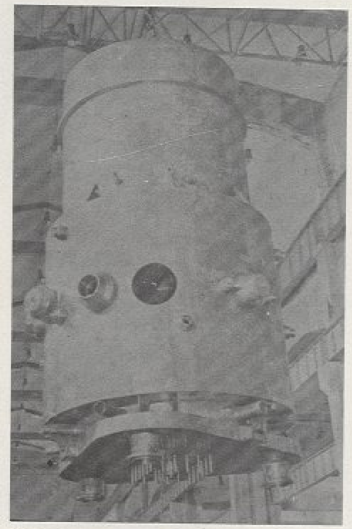
Calandria: Calandria, the heart of the DHRUVA reactor, was fabricated from extra low carbon stainless steel plates ranging in thickness from 19 mm to 65 mm. It consists of a triangular inlet plenum with 144 fuel cups at the bottom and circular plenum with a corresponding number of lattice positions at the top separated by a main shell of approximately 3750 mm in diameter. The overall height of the calandria is 6700 mm.

In order to meet the close tolerance and high quality requirements, many new and advanced techniques were employed in the manufacture of the calandria. One such technique involved the use of electron beam welding technology for welding the fuel cups and lattice tubes. Besides the advanced machining and inspection techniques, accurate optical alignment techniques were also developed during the course of the job. Use of these new techniques, special fixtures and toolings in the manufacture also enabled Central Workshops to deliver the calandria ahead of the scheduled time.

Coolant Channel Assemblies: DHRUVA calandria has 144 lattice locations in which coolant channel components are assembled. A coolant channel assembly consists of (i) Fuel channel anchor (ii) Guide tube (iii) Extension tube (iv) Stump tube (v) Anti-torque collar (vi) Seal cap (vii) Dust cap.

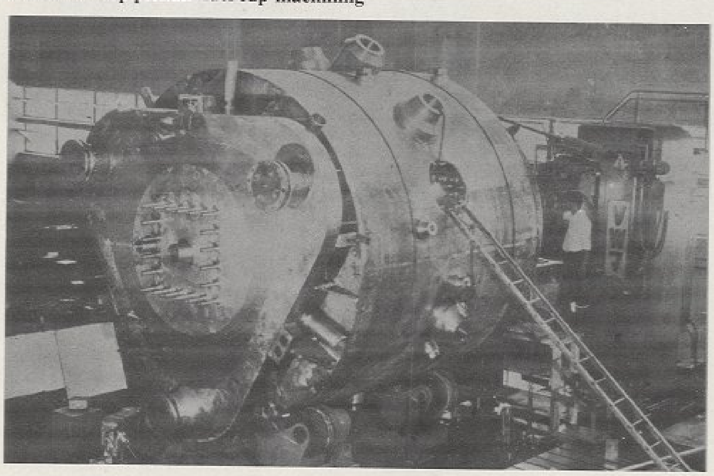
The Workshops undertook the manufacture of 152 numbers of the above assembly components (in SS 304L) except the anti-torque collar and the zircalloy tube which forms part of the 9.2 m long assembly. The manufacture called for sophisticated production techniques to achieve the exacting tolerances. Guide tubes with outer diameters varying from 100 to 116 mm and 5214 mm long have precision deep bores, internal spherical grooves, keyways, slots etc. A special purpose machine and a precision welding rotator were developed in the Workshops for the manufacture of these components. Stump-tube and extension-tube assembly with outer dia 112 to 146 mm and 5289 mm long have precision deep bores, key slots and a nozzle. An indigenously built SPM alongwith deep hole boring and honing facility and precision welding rotator were employed to manufacture the stump-tube, extension-tube assemblies.

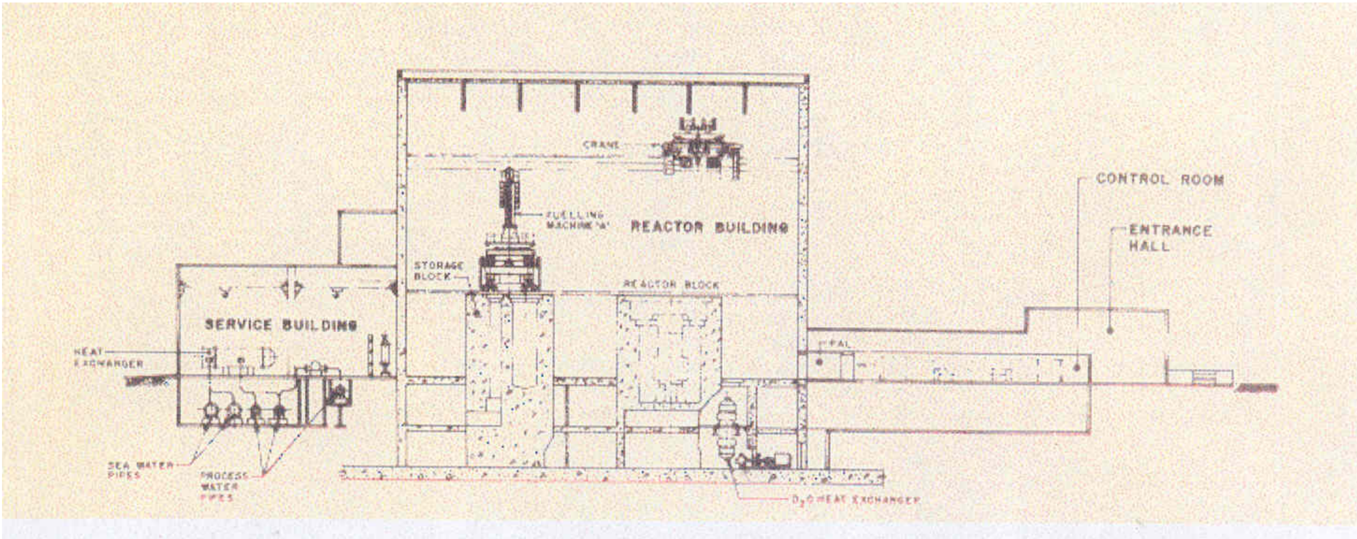
Storage shield blocks: Seven types of blocks weighing between 2 to 15 tonnes,



Calandria assembly

Calandria top plenum fuel cup machining

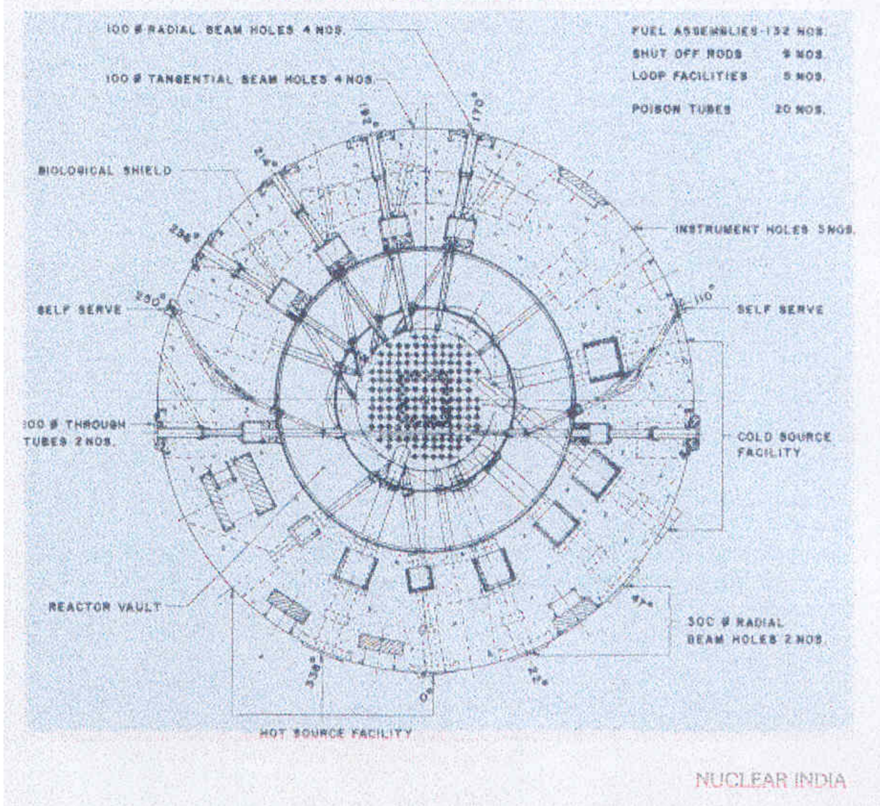




Sectional elevation

Source: Department of Atomic Energy, "India's Indigenous Reactor DHRUVA," *Nuclear India*, Vol. 23/Nos. 11&12/1985, p. 14.

Reactor experimental facilities



Source: Department of Atomic Energy, "India's Indigenous Reactor DHRUVA," *Nuclear India*, Vol. 23/Nos. 11&12/1985, p. 6.

CANDU-6 reactor vessel in transit.
Source: AECL, "CANDU-6, Proven Technology for the 21st Century,"
http://www.aecl.ca/AssetFactory.aspx?did=231

In the 40 MWt-class NRX and CIRUS designs the calandrias are quite thin and are made of aluminum in order not to strongly absorb neutrons. This is because the graphite neutron reflector, which surrounds the calandria, is used to reflect escaping neutrons back into the calandria where the reactor fuel is located. The rings shown in the Quickbird satellite image are not thin and are surely not aluminum. In contrast, the thermal shields for a CIRUS-type reactor are relatively thick (~ 0.3 m) and are made of cast iron, which would appear dark toned, similar to the color of the rings in the satellite image.

As noted above the calandria of the 100 MWt-class DHRUVA reactor is made of stainless steel. Its thickness ranges from 1.9 cm to 6.5 cm, which is considerably thinner than the rings observed in the satellite image of Khushab II. Although the outer diameter is not uniformly the same and could appear thick in a satellite image were it assembled on site (which was not how DHRUVA was assembled), the stainless steel would unlikely show as dark in color.

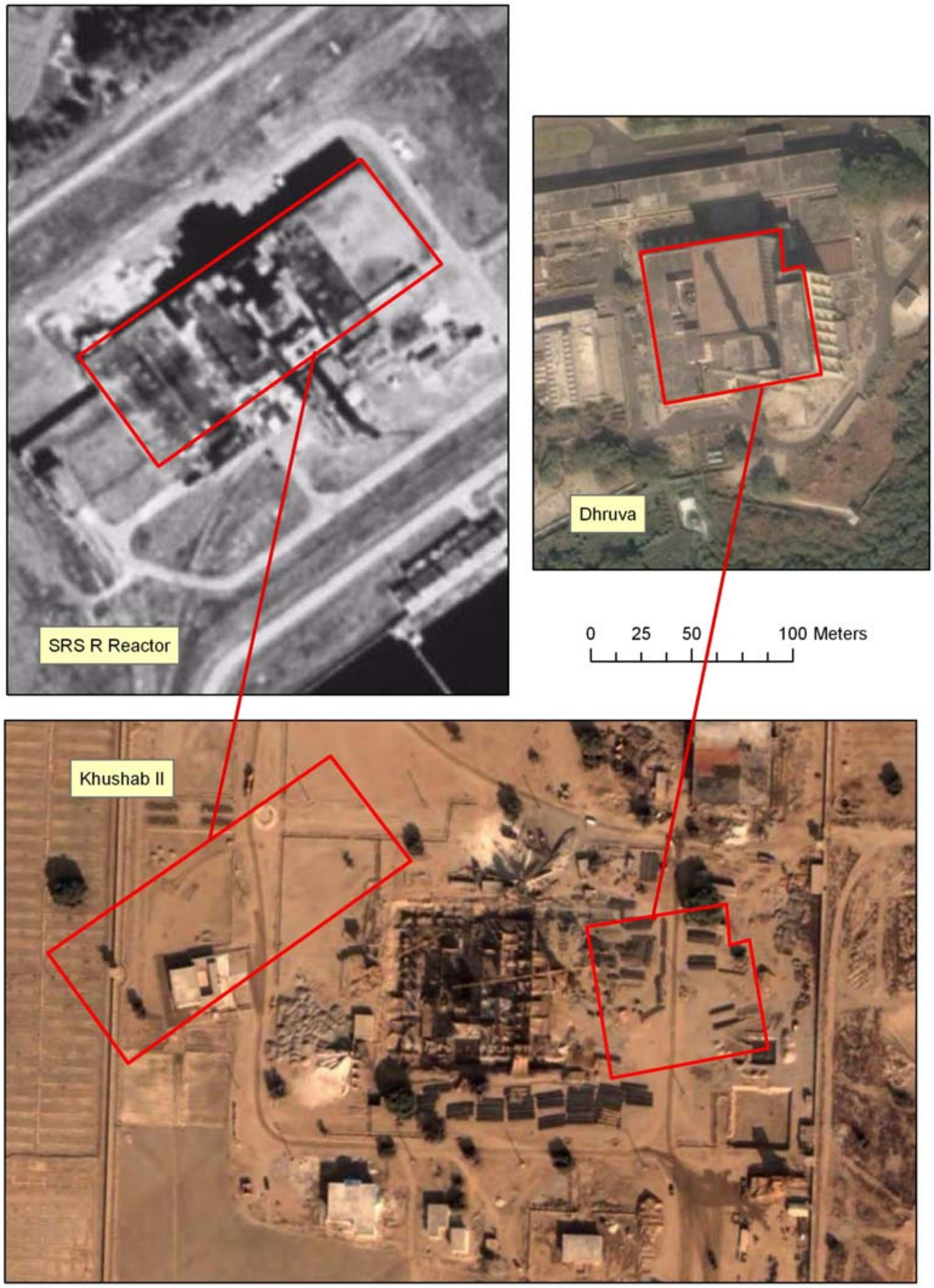
The Reactor Building

Next we examine what can be deduced from the size of the reactor building. As previously noted, we agree with ISIS that the size of the reactor building is a poor indicator of the reactor's power.

Pakistan's Khushab I reactor can be seen on Google Earth at coordinates: 32 01 12.7N, 72 12 27.1E. It is similar to India's CIRUS reactor at 19 00 28.1N, 72 55 05.9E. Both Khushab I and CIRUS are 40 MWt-class reactors. Pakistan's Khushab II reactor, under construction at coordinates 32 00 30.4N, 72 10 20.0E, can also be seen on Google Earth. Its external shape is similar to India's 100 MWt DHRUVA reactor at 19 00 29.4N, 72 55 11.4E. Aerial photography images of the five SRS production reactors can be viewed on Microsoft's Terraserver web site (http://terraserver.microsoft.com/image.aspx). The reactors are located at:

Reactor	Latitude, Longitude	Terraserver entries are in decimal degrees Longitude	Latitude
R	33 16 28N, 81 34 46W	-81.57944	33.27444
C	33 15 00N, 81 40 36W	-81.67667	33.25000
L	33 12 41N, 81 37 24W	-81.62333	33.21139
K	33.12 41N, 81 39 50W	-81.66389	33.21139
P	33 13 43N, 81 34 52W	-81.58111	33.22861

The Khushab II reactor building is about 65 m x 70 m = ~4,550 m^2. DHRUVA's footprint is just over 5,000 m^2. As indicated in the following figures (p. 13), both are less than one-half the size of the R-Reactor building at SRS. This comparison suggests that power output of Khushab II is more likely to be closer to that of DHRUVA rather than that of the SRS production reactors.



Images of the Khushab II, DHRUVA and R-Reactor, reproduced at the same scale.

The Reactor Hall

We have also compared the size of the reactor halls, i.e., the respective rooms within the reactor buildings where the reactor vessels are located. It is clear that the size of the rooms do not scale with reactor power. The size of the Khushab II reactor hall, as measured in the Google Earth image, is about 20 m x 30 m = ~ 600 m^2. The DHRUVA reactor hall is a massive concrete structure 46 m x 35 m = 1,472 m^2 (and 32 m in height), or more than twice the floor space of Khushab II reactor hall.

As indicated in the figure on the following page (p. 15), the reactor hall of at least one of the U.S. Savannah River Site ("SRS") heavy water production reactors appears to be only about 19 m across inside.[15] This suggests that the reactor hall floor space of a typical SRS reactor is less than that of DHRUVA, even though the maximum power of the SRS reactors was eventually increased to more than twenty times that of DHRUVA. This confirms that size of the reactor hall is not an indicator of the reactor's power.

Heat Dissipation

We now turn to the issue of heat dissipation. The Khushab climate is a semi-arid with hot summers and mild winters. As can be seen in Google Earth imagery, at the Khushab I site there is a modest mechanical-draft cooling facility adjacent to and servicing this 40 MWt-class reactor. It is approximately 58 m in length and 10 m wide and consists of 8 cells. A late-1950s Russian estimate indicates that mechanical draft cooling towers dissipate up to 80,000 to 100,000 kcal/m^2-hr(0.093-0.116 MWt/m^2)[16] These Russian data, are consistent with Khushab I being a 40 Mt-Class reactor, particularly given that the Russian data may overestimate the cooling capacity at Khushab, where the climate is more challenging.

The Khushab II reactor site is rectangular and about 100 acres in size—comparable to the 120 acre circular Khushab I reactor site nearby. There is room at the Khushab II site for a cooling facility comparable to the one at Khushab I, but Khushab II most likely would have to uses an entirely different cooling technology to accommodate the cooling

[15] This figure can also be found in E.I. du Pont de Numours & Co., Savannah River Laboratory, "Environmental Information Document: L-Reactor Reactivation," DPST-81-241, April 1982, Figure 3.1-3, p. 3-5.

[16] L.D. Berman, *Evaporative Cooling of Circulating Water* (Oxford: Pergamon Press, 1961), p. 263.

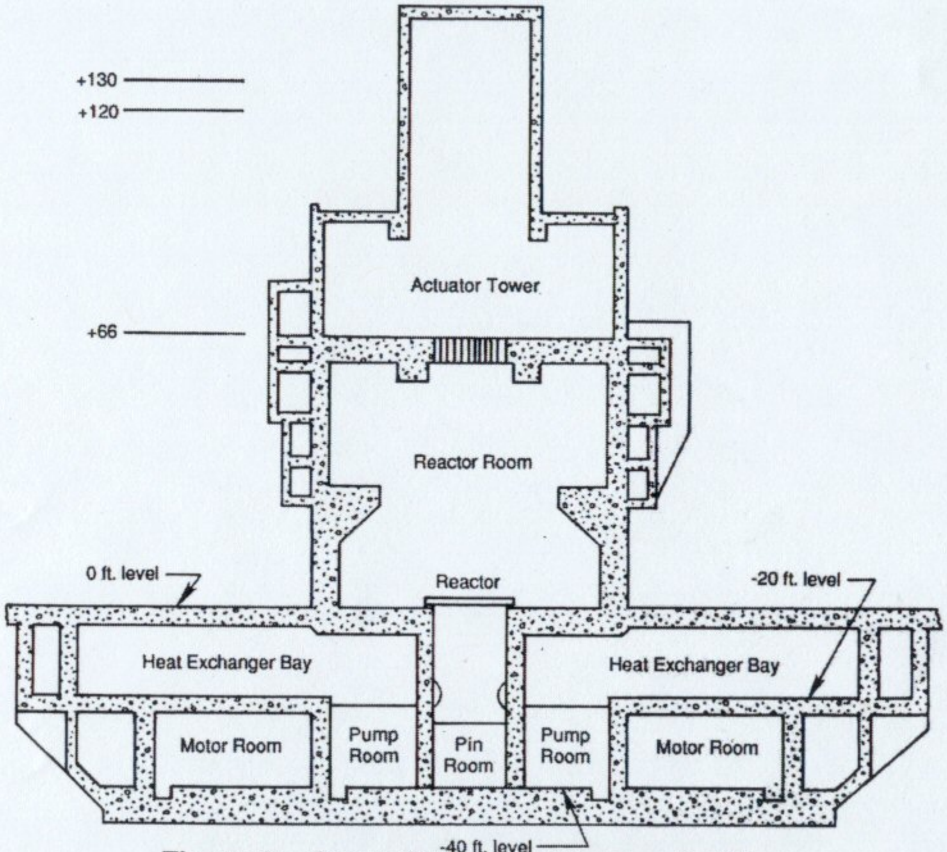


Figure 8 – Cross Section of Reactor Building

Figure 8, p. 28, History of DuPont at the Savannah River Plant, by W. P. Bebbington (1990).

Motor Room:	37.5	ft.
Pump Room:	20	ft.
Pin Room:	17	ft.
Heat Exchanger Bay	82	ft.
Reactor	17	ft.

requirements for a reactor operating at 1,000 MWt, or greater.[17] Space is available as evidenced by the six 30 m-diameter cooling towers serving the 3,323 MWt WPPS-Unit 2 at the Hanford Reservation in Washington (see p. 17). It is questionable whether two such massive towers, which would be needed to service a 1,000 MWt reactor, will be built at the Khushab II reactor site.

After the construction of the Khushab II cooling system—perhaps in the next year or so— we should be able to resolve any lingering question regarding the size of Khushab II reactor. If another mechanical draft cooling tower system with 8 to 16 cells, each about 70 m^2, is constructed at Khushab II, this will provide strong evidence that Khushab II will operate in the 50-100 MWt range.

Summary

We agree with ISIS that the size of the reactor building is a poor indicator of the reactor's power and that a better indicator is the size of the reactor vessel. However, the design of other heavy water reactors does not support the ISIS argument that the thick dark ring seen in the satellite images of Khushab II under construction is the reactor vessel. The dark ring is more likely a thick iron radiation shield within which the reactor vessel, or calandria, will be placed.

Contrary to the assumption of ISIS, none of the heavy water reactor vessels that we have examined were assembled in the field before construction of the reactor vault. The power level of Khushab II is more likely to be at least as large as the 40 MWt-Class Khushab I, but less than that of the 100 MWt-Class DHRUVA reactor. The Khushab II reactor site can readily accommodate a mechanical draft cooling system similar to that at Khushab I. Installation of a different cooling technology necessary to meet the cooling requirements of a reactor operating at power levels 20 times higher is possible. An estimate of the cooling capacity can be made after construction of the Khushab II cooling system commences—perhaps in the next year or two.

---

[17] At SRS the L-, K- and C-Reactors, which eventually typically operated at 2,150 MWt (L-Reactor), each required 11.3 m3/sec (180,000 gallons per minute ("gpm") of secondary cooling water flow through the reactor even while operating at a high water discharge temperature (70-80 degrees C). If operated at 1,000 MWt each would require a flow rate of about 5 m3/sec (80,000 gpm). DOE, "Environmental Assessment, L Reactor Operation, Savannah River Plant," DOE/EA-0195, August 1982, pp. 2-5 and 4-2; DOE, "Draft EIS, Alternative Cooling Water Systems, Savannah River Plant, Aiken, South Carolina," DOE/EIS-0121D, March 1986, pp. 2-13 and 2-31.

When the U.S. Department of Energy proposed to restart the SRS L-Reactor in the 1980s it considered several cooling alternatives, including the construction of a 1,000-acre cooling lake (L-Lake) and a 500-acre lake with spray cooling. U.S. Department of Energy, "Final Environmental Impact Statement: L-Reactor Operation, Savannah River Plant," DOE/EIS-0108, May 1984, Vol. 2, Appendix I.

Six large cooling towers serving Washington Public Power Station's Unit -2 (3323 MWt) at Hanford Reservation, Washington [46 28 17N; 119 19 59E].

Finally, it is worth noting that since the power level, and therefore also the plutonium production rate, of Khushab II will at least be as large as that of Khushab I, there is no dispute that Khushab II will permit Pakistan to at least double the rate of production of nuclear weapons containing plutonium. Pakistan's initial route to weapons was though uranium enrichment. to which it then added a plutonium production capability. By combining the two materials, in what is called a composite core (a smaller plutonium sphere encased in a shell of highly enriched uranium) Pakistan could make more bombs than if it made plutonium and uranium cores separately.

The idea has been around for more than 60 years. A few days after the Trinity test of July 16, 1945, during World War II, the U.S. considered using some or all of the approximately 60 kilograms of HEU intended for Little Boy in order to increase the number of available bombs, but General Leslie R. Groves, head of the Manhattan Project, rejected the idea. Three tests carried out as part of Operation Sandstone were conducted in April and May of 1948. Second-generation warhead design concepts were validated using composite cores and levitation principles in the X-Ray and Yoke tests and an all U-235 levitated core in the Zebra test. As recounted in an official Air Force history, "the immediate result was to make possible within the near future a 63 percent increase in the total number of bombs in the stockpile and a 75 per cent increase in the total yield of these bombs."[18] Thus, it is prudent to assume that Pakistan's nuclear weapons constructed from Khushab I and II plutonium may contain as little as two to three kilograms of plutonium and not twice this amount as assumed by ISIS and others attempting to estimate the future rate of weapon production by Pakistan.

[18] *The History of Air Force Participation in the Atomic Energy Program, 1943-1953*, Volume II, Part Two, p. 694.