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High-Enriched Uranium Production for South African Nuclear Weapons

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Abstract:

We estimate that South Africa has on hand 731 ± 24 kilograms of about 90%-enriched uranium. This amount could be used to construct 12 Hiroshima type fission bombs. The South African government maintains it constructed only six such devices, and never intended to construct more than seven. There is an additional inventory difference equivalent to two bombs worth of material. Implosion type devices were apparently being researched at the time the nuclear weapons program was dismantled. Had this effort been continued, eventually South Africa would have been able to construct four times as many weapons from the same amount of fissile material.

Introduction:

South Africa formerly decided to build a nuclear deterrent capability in 1974. It constructed the first of six gun assembly type nuclear weapons using South African produced high-enriched uranium (HEU), before deciding in 1989 to dismantle its nuclear weapons program, and to accede to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT). South African officials have since revealed to the International Atomic Energy Agency (IAEA) extensive data related to its enrichment plant operations, but has maintained it is not in the interest of non-proliferation to publicly reveal the amount of HEU produced or on-hand, since it is stored in a single location. Since South Africa has revealed already that there is at least six bombs worth of material in storage, it hardly makes sense to keep secret how much additional material is on hand. From the standpoint of non-proliferation, a thorough understanding of the material accounting discrepancies is more important. One should, therefore, know how much weapon material was produced. Before making such an estimate, we review briefly the history of the South African nuclear program.

Overview of South Africa's Nuclear Program:[1]

South Africa's involvement in the nuclear field began shortly after World War II as a supplier of uranium to the nuclear weapons programs in the United States and Great Britain.[2] With extensive uranium resources, by 1955 South Africa was operating nineteen mines and twelve extraction plants.[3] In 1957 South Africa participated in the establishment of the IAEA and was given a permanent seat on its board of governors, as the country with the "most advanced"

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[1] For more thorough treatments of the history of South Africa's nuclear program, see: Leonard S. Spector, with Jaqueline R. Smith, *Nuclear Ambitions*, (Boulder, CO: Westview Press, 1990); Leonard S. Spector, *Nuclear Proliferation Today*, (New York: Vintage Books, A Division of Random House, 1984); *Nuclear Proliferation Today*, (New York: Vintage Books, 1985); and David Albright, Frans Berkhout, and William Walker, *World Inventory of Plutonium and Highly Enriched Uranium 1992*, (Oxford: SIPRI and Oxford University Press, 1993).

[2] Spector, *Nuclear Proliferation Today*, 1984, p. 279.

[3] Ibid., p. 280.

nuclear program in the region.[4] The United States and South Africa signed a nuclear cooperation agreement in the same year, and shortly thereafter South Africa embarked on a civil nuclear research program, focusing initially on development of a locally designed power reactor and development of a uranium enrichment capability.[5] The power reactor project was terminated after a short time because of a lack of resources.[6] Under the 1957 nuclear cooperative agreement, the United States sold South Africa a five megawatt-thermal (Mw_t), HEU-fueled research reactor called Safari-I. Located at the National Nuclear Research Center at Pelindaba, construction commenced in 1961, and it began operating under IAEA safeguards in 1965.

In 1967 South Africa commissioned a second, smaller reactor, Pelunduna-Zero (Safari-II), which used low-enriched uranium (LEU) and heavy water. Also under IAEA safeguards, the United States supplied it with 606 kilograms (kg) of 2%-enriched uranium. The plant has since been decommissioned.[7]

Desiring to add value to their uranium export product, the formal decision to start the enrichment project was made in secret in 1967.[8] In the following year South Africa refused to sign the just-completed NPT, voicing the common argument that the treaty did not obligate the weapon-states to reduce their arsenals, and also expressing concern over the treaty's impact on the commercial aspects of nuclear energy in South Africa.[9] In 1970 the state controlled Uranium Enrichment Corporation (UCOR) was established to build the enrichment plant;[10] and in July of the same year Prime Minister John Vorster announced to parliament that the South African Atomic Energy Board had successfully developed a new process, "unique in its concept," of uranium enrichment.[11]

In March 1971 the Ministry of Mines approved research work on peaceful nuclear explosives for the mining industry. The South African Atomic Energy Corporation (AEC) took responsibility for development and production.[12]

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[4] Spector *Nuclear Ambitions*, p. 270. President Eisenhower had launched the "Atoms for Peace" program in his speech before the United Nations on 8 December 1953.

[5] Waldo E. Stumpf, "South Africa's Limited Nuclear Deterrent Programme and the Dismantling Thereof Prior to South Africa's Accession to the Nuclear Non-Proliferation Treaty," a presentation at the South African Embassy Annex, Washington, D.C., 23 July 1993. Dr. Stumpf is Chief Executive Officer of the Atomic Energy Corporation of South Africa. A transcript of his talk, but not copies of his slides, has been released by the South African Embassy.

[6] Ibid.

[7] Spector, *Nuclear Proliferation Today*, 1984, p. 281.

[8] Stumpf, "South Africa's Limited Nuclear Deterrent Programme."

[9] Spector, *Nuclear Proliferation Today*, 1984, p. 283.

[10] Stumpf, "South Africa's Limited Nuclear Deterrent Programme."

[11] Spector, *Nuclear Proliferation Today*, 1984, p. 284.

[12] *The Arms Control Reporter*, May 1993, p. 455.B.81.

Its security threatened by a declared policy of Warsaw Pact countries to expand their influence in Southern Africa, and by a buildup of Cuban troops in Angola, the South African government in 1974 formally decided to seek a limited nuclear deterrent.[13] Building 5000 at Pelindaba was probably the site of early nuclear weapons manufacture.[14] Approval was given for a nuclear test site in the Kalahari desert, and the first stages of the Y-plant, a pilot scale uranium enrichment plant at Valindaba based on the gas nozzle technology, were commissioned.[15] South Africa refused to place it under IAEA safeguards.

In response to South Africa's acquisition of the Valindaba plant and strong congressional pressure, the Ford Administration in early 1975 suspended Safari-I fuel exports. The last export of U.S. origin fuel was in November 1975. In the same year South African Atomic Energy Board President A.J.A. Roux announced that his country would build a commercial-scale enrichment plant with most of its product intended for export.[16] By 1978, however, the decision was made to build a smaller facility, said to be capable of producing 75 metric tonnes (t) of LEU per year, still 50 percent more than needed to refuel the two Koeberg nuclear power plants that Pretoria purchased from France in 1975.[17] In 1977, in order to conserve fuel the Safari-I power level was reduced from 20 Mw_t to 5 Mw_t.[18]

Three shafts were drilled at the Kalahari test site to a depth of 180 to 200 meters, because three devices were intended for demonstration. One shaft was abandoned due to geological conditions. The other two were completed in 1977.[19] On August 6, 1977 the Soviet Union alerted the United States to the construction activities at the Kalahari test site. Extensive pressure on the South African government by the superpowers, France Great Britain, and West Germany

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[13] Stumpf, "South Africa's Limited Nuclear Deterrent Programme." The program was code-named Kraal--an Afrikaans word for the stone walls used to fence in cattle; *The Arms Control Reporter*, May 1993, p. 455.B.77.

[14] *The Arms Control Reporter*, May 1993, p. 455.B.82.

[15] Stumpf, "South Africa's Limited Nuclear Deterrent Programme." The Y-plant uses an aerodynamic separation process similar to that developed by Becker in West Germany. It is described more fully in Manson Benedict, Thomas Pigford, and Hans Levi, *Nuclear Chemical Engineering*, (New York: McGraw-Hill Book Company, 1981), pp. 876-895. Contrary to some reports, it does not use the Helikon cascade technique that was incorporated into the Z-plant. Valindaba is a Zulu word meaning 'we don't talk about this at all;' *The Arms Control Reporter*, May 1993, p. 455.B.77.

[16] Spector, *Nuclear Proliferation Today*, 1984, p. 290, who cites Robert S. Jaster, "Politics and the 'Afrikaner' Bomb," *Orbis*, Winter 1984, p. 28, claims Roux "announced that his country would build a commercial-scale plant capable of producing five thousand tons of low-enriched uranium per year." To produce 5000 tonnes of 3.25% enriched LEU, at a tails assay of 0.3%, would require 20 million SWU, on the order of the total U.S. enrichment capacity at its peak. If, as seems more likely, the intention was to enrich annually the uranium in 5000 tons of U_3O_8, then only 2 million SWU annually would be required--to produce 540 tonnes of 3.25% enriched LEU annually, at 0.3% tails.

[17] Ibid. and Spector *Nuclear Ambitions*, p. 277.

[18] Stumpf, "South Africa's Limited Nuclear Deterrent Programme."

[19] *The Arms Control Reporter*, May 1993, p. 455.B.80.

forced South Africa to abandon the test site. The shafts at Kalahari were inspected once again in 1987 in response to Cuban successes in Angola.[20]

Also in 1977, the Y-plant operated as a cascade for the first time;[21] and commenced HEU production in January 1978.[22] Toward the end of 1978, the Y-plant first began producing HEU, which in turn was converted into metal, molded and machined into weapon parts, and fitted into the first nuclear weapon.[23] The uranium was relatively impure and enriched only to about 80% in the isotope U-235. The uranium was later removed and recycled through the enrichment plant to clean it up and upgrade the enrichment.[24] In 1979 a decision was made by the head of government that Armscor should produce the nuclear devices, and that the role of the AEC would be limited to uranium enrichment and some neutron physics calculations.[25] The second nuclear weapon was provided with HEU in the same year.[26] Advena, the secret Armscor facility at Kentron Circle, 25 kilometers west of Pretoria, where most of the subsequent weapons work took place here, was commissioned in 1980 and completed the following year.[27] In 1985 the government decided to limit the size of its nuclear arsenal to seven nuclear weapons.[28]

An accident in 1979, caused by a catalytic reaction of the two gases used in the enrichment process--uranium hexafluoride (UF_6) and hydrogen--forced the Y-plant to shut down for 18-23 months.[29] HEU production resumed in 1981. In this same year, South Africa announced the successful development of 45%-enriched fuel for the Safari-I reactor. From that point onward South Africa supplied its own fuel for Safari-I.[30]

All South African HEU was produced in the Y-plant. Construction of the second enrichment plant--the semi-commercial Z-plant--was begun in 1979. It was commissioned in 1984,

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[20] Stumpf, "South Africa's Limited Nuclear Deterrent Programme."

[21] Ibid.

[22] Albright, Berkhout, and Walker, *World Inventory of Plutonium and Highly Enriched Uranium 1992*, p. 186.

[23] Stumpf, "South Africa's Limited Nuclear Deterrent Programme."

[24] Ibid.

[25] Ibid.

[26] Ibid.

[27] Stumpf, "South Africa's Limited Nuclear Deterrent Programme."

[28] Ibid.

[29] Stumpf, "South Africa's Limited Nuclear Deterrent Programme,"said the plant was down for about 18 months. Albright, Berkhout, and Walker, *World Inventory of Plutonium and Highly Enriched Uranium 1992*, p. 186, report that production halted from August 1979 until July 1981, a total of 23 months.

[30] Stumpf, "South Africa's Limited Nuclear Deterrent Programme."

and produced its first LEU in August 1988.[31] The Z-plant, with 56 modules each containing about 500,000 separating elements, has been configured such that the enrichment level is limited to less than 5% U-235.[32] As of the end of 1991, the plant could operate at its optimum production of 300,000 kg SWU per year.[33] It has been used solely for the production of LEU, providing fuel for the two Koeberg power reactors that started up in July 1984 and November 1985, respectively.

Needing some 3.25%-enriched uranium for the first four test assemblies of Koeberg reactor fuel produced by UCOR, the Y-plant was reconfigured in 1986 to produce LEU. It operated in this mode for about eleven months.[34]

In September 1989, barely one or two weeks in office, President Frederik W. de Klerk ordered the nuclear weapons program to be terminated. Plans were drawn up, and on February 26, 1990, President de Klerk provided written instructions to start the dismantlement process.[35] Instructions were given the following day to dismantle the six completed nuclear weapons--to destroy the non-nuclear hardware, destroy the technical documentation, recast the HEU and return it to the Atomic Energy Corporation (AEC), and neutralize the Armscor facility before acceding to the NPT.[36] The Y-plant stopped producing HEU in 1989, and ceased operations on February 1, 1990.[37] In early July 1991, the last weapon, the sixth device, was dismantled. The seventh nuclear weapon that was commissioned, was never built.[38] The Armscor facility was decontaminated and returned back to the AEC, and switched to making medical equipment.[39] South Africa acceded to the NPT on 10 July 1991.

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[31] Ibid.

[32] Ibid. The Z-plant also uses the aerodynamic, or jet nozzle process, and incorporates the Helikon cascade technique permitting several separation stages to be incorporated in a single module. See Benedict, Pigford, and Levi, *Nuclear Chemical Engineering*, pp. 893-895, for details.

[33] Albright, Berkhout, and Walker, *World Inventory of Plutonium and Highly Enriched Uranium 1992*, p. 187.

[34] Stumpf, "South Africa's Limited Nuclear Deterrent Programme."

[35] Ibid.

[36] Ibid.

[37] Ibid.

[38] Ibid.

[39] Ibid.

BOX:

Key Milestones in the Operation of the Y-plant:

1974	first stages of the plant were commissioned
1977	first operation of enrichment cascades
1978	first production of HEU toward the end of the year
1979	production stopped for 18-23 months due to process failure
1981	HEU production resumes
1986	Y-plant reconfigured and used for about 11 months to produce LEU (3.25%-enriched fuel for the Koeberg reactors)
1989	in September a decision was made to stop HEU production
1990	plant ceased production on 1 February

Estimating HEU Production:

As noted previously, South African officials have publicly revealed some additional data related to enrichment operations, but not the amount of HEU produced for weapons. We can estimate the latter using equations that relate the amount of enrichment plant feed material, enriched product, depleted uranium tails, and separative work.[40]

During its 14-15 year history,[41] the Y-plant was shut down for 18-23 months, produced LEU for about 11 months, and produced HEU for about 101-106 months (8.4 to 8.8 years).[42] The South African AEC has publicly revealed the average U-235 assay of the natural uranium feed (X_F), which is the same as that of most uranium deposits throughout the world; the average assay of the depleted uranium tails (X_T); the uncertainty (one standard deviation) in the tails

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[40] In what follows, one must differentiate between (a) the declared amount of HEU on hand--presumably reported by South Africa to the IAEA, and subject to conformation by direct measurement; and (b) South Africa's estimate of the amount of HEU produced, when calculated using material balance equations and measured values of product and tails inventories and U-235 assays. Alternatively, the declaration (a) and estimate (b) can be given in terms of the amount of U-235 in the HEU, labeled (c) and (d), respectively. Since South Africa has not revealed (a)-(d) publicly, except for the uncertainty in (d); we will be making our own estimates, (e)-(h), of the South Africa's measurements and best estimates, (a)-(d). Each of our best estimates has a corresponding uncertainty.

[41] From 1975 to 1 February 1990.

[42] From late-1978 to 1 February 1990, less 18-23 months, during 1979-1981, when the plant was down, and 11 months, 1986 to 1987, when the plant was producing LEU.

assay (δX_T), and the calculated two standard deviation uncertainty in the estimate of the amount of U-235 in the HEU ($2\delta[X_H H]$):[43]

X_F = 0.00711 (i.e., 0.711% U-235).
$X_T \pm \delta X_T$ = 0.00456 ± 0.00071
$2\delta[X_H H]$ = 526 kg.

The South African AEC made precise measurements of the amount of HEU and LEU, and the U-235 assays of each. Little attention, however, was paid to the depleted uranium tails. It was not weighed or assayed accurately. The tails are stored as UF_6 in some 600 cylinders, filled in layers, typically five of six layers per cylinder. Over the operating history of the plant the tails assay varied from 0.2% to 0.6% U-235. The uncertainty in the tails assay, therefore, dominates the uncertainty in the calculated inventory of HEU.

We start with the mass balance equations for total uranium and for U-235:

$$F = H + L + T, \tag{1}$$

and

$$X_F F = X_H H + X_L L + X_T T, \tag{2}$$

where F, H, L, and T are the feed, HEU product, LEU product, and tails, respectively, and X_i are the respective U-235 assays. Substituting (1) into (2), and solving for $X_H H$ gives

$$X_H H = X_H[(X_F - X_T)T - (X_L - X_F)L]/(X_H - X_F). \tag{3}$$

In passing, we also note that if there were only one enriched product, H, equation (3) would read:

$$X_H H = X_H[(X_F - X_T)/(X_H - X_F)]T_H. \tag{4}$$

The uncertainty in $X_H H$, $\delta[X_H H]$, is approximated by applying to equation (3) the general relationship[44]

$$\delta[X_H H]^2 = \left(\frac{\partial[X_H H]}{\partial X_F}\right)^2 \delta[X_F]^2 + \left(\frac{\partial[X_H H]}{\partial X_T}\right)^2 \delta[X_T]^2 + \ldots \tag{5}$$

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[43] Stumpf, "South Africa's Limited Nuclear Deterrent Programme." $\delta[X_H H]$ is calculated from measured product, other than HEU, and tails assays and amounts. Here, it is not measured directly.

[44] See, for example, Philip R. Bevington, *Data Reduction and Error Analysis for the Physical Sciences*, (New York: Mc Graw-Hill Book Co., 1969), p. 60.

Since the uncertainty in the tails assay, X_T, dominates the uncertainty due to the other parameters, then equation (5) reduces to:

$$\delta[X_H H]^2 \approx \left(\frac{X_H T}{X_H - X_F}\right)^2 \delta[X_T]^2 , \qquad (6)$$

Dividing the square root of (6) by (4) yields

$$\delta[X_H H]/(X_H H) \approx (\delta[X_T]/(X_F - X_T))(T/T_H), \qquad (7)$$

which can be rewritten

$$X_H H \approx (\delta[X_H H]/\delta[X_T])(X_F - X_T)(T_H/T). \qquad (8)$$

An upper limit on the amount of U-235 in the HEU product can be found by setting $T_H = T$; giving $X_H H < 945$ kg. Later we will be able to show that $T_H/T = 0.792$, in which case $X_H H \approx 748 \pm 256$ kg.

Responding to press reports concerning IAEA and U.S. government efforts to reconcile the inventory data, the South African AEC revealed publicly that the calculated two standard deviation uncertainty in the U-235 in the HEU product, i.e., $2\delta[_H H] = 526$ kg, was over five times the "actual discrepancy."[45] This would not be an issue unless the amount of HEU the South Africa reported to the IAEA as being on hand was less than that estimated from the tails and other inventories using the mass balance equations. In other words, we know the sign of the discrepency; and its magnitude is less than 105 kg (=526/5), and probably greater than 88 kg (=526/6).[46] Therefore, by this estimate, the amount of U-235 in the HEU product that South Africa presumably reported to the IAEA as being on hand is between 643 and 660 kg.

We do not know the average value of X_H, and in fact all of the HEU may not be of the same U-235 assay. Nevertheless, we can convert the results into 90% U-235 equivalence, in which case we can say that South Africa enriched HEU equivalent to the production of 714 to 733 kg of 90%-enriched uranium.

Although not publicly revealed, we know from other sources the South African estimate of the amount of depleted uranium tails from Y-plant operations, namely, 370,643 kg; and we will use this in subsequent calculations. This figure also provides a useful check on the validity of our assumption that the uncertainty in the tails assay dominated other uncertainties, i.e., the validity of equation (6). Rewriting equation (6), we estimate that

$$T \approx (\delta[X_H H])(1 - (X_F/X_H))/(\delta X_T) \qquad (9)$$

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[45] Stumpf, "South Africa's Limited Nuclear Deterrent Programme." We infer that "actual discrepancy" is the difference between the amount of U-235 in the HEU, as calculated from the measured inventories and assays of tails, scrap, and enrichment products, other than the weapons HEU, and the amount of U-235 in the HEU on hand as measured directly.

[46] We infer this, since the 526 kg figure was not reported as being more than six times the "actual discrepancy." The "actual discrepancy," of course, could be even less than 88 kg.

$\approx$ 367,000 kg,

which agrees well with the 370,643 kg South African estimate.

The amount of HEU production also can be estimated directly from the tails inventory, and the feed, product and tails assays. To do so we must first subtract the amount of tails associated with start-up of the plant, i.e., bring the plant up to equilibrium condition, and production of fuel for Safari-I and the two Koeberg reactors.

Tails Withdrawal During Start-up: During start-up, tails are withdrawn prior to product withdrawal. Consequently, some tails are produced with no associated product. The equilibrium, or start-up, time for product withdrawal, t_P, is defined as the number of days of equivalent production lost during the approach to steady state.[47] The equilibrium time for tails withdrawal, t_T, is similarly defined. The difference in these two times, $(t_P - t_T)$, times the rate of tails production at equilibrium, gives the amount of tails produced for which there is no associated product. Benedict, Pigford, and Levi give approximate equations for the start-up times.[48] Their approximation for t_P is:

$$t_P = \frac{8\,h}{(1 - \alpha)^2}\, f(X_P, X_P)\,, \tag{10}$$

where h, the *stage holdup time*, is defined as the time it takes material to flow through one stage; α is the stage separation factor; and $f(X_P, X_P)$ is a function of the product and feed assays. The value of $(1 - \alpha)$ for Y-plant is 0.027, or greater-- an order of magnitude greater than that for gaseous diffusion, $(1 - \alpha) = 0.003$.[49] Unfortunately, we do not know h, the stage holdup time, for the Y-plant. We have been told by U.S. enrichment experts that it could be quite large--larger than that of a gaseous diffusion plant. We therefore assume that the start-up time for the Y-plant is less than that of a gaseous diffusion plant producing HEU, but it may not be much less. It has been reported that Y-plant started up in January 1978, and began producing HEU toward the end of that year. But we do not know what fraction of this period was associated with getting the bugs out of the system, and what fraction was bringing the plant up to equilibrium. Lacking better information we assume the start-up period was 3 ± 2 months.

Following the 1979 accident, the start-up process would have been repeated. We do not know what fraction of the in-plant inventory was recovered and recycled. The accident has been described as "catastrophic," suggesting a large fraction of the in-plant inventory was not recycled. We assume 1.5 ± 1.5 months of additional tails were produced during this second start-up. Taken into account both start-up periods, we therefore assume 4 ± 2 percent, or 15,000 ± 7500 kg of

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[47] Benedict, Pigford, and Levi, *Nuclear Chemical Engineering*, pp. 678-679.

[48] Ibid., equation 12.204 on p. 681, and equation 12.209 on p. 682.

[49] Ibid., p. 895.

tails were associated with production of in-plant inventory during which there was no product produced.[50]

Had the Y-plant been devoted entirely to HEU production, after start-up it could have produced about 1000 kg of 90%-enriched uranium.[51]

Fueling Safari-I and the Koeberg Reactors: As noted above, in 1981 South Africa began supplying 45%-enriched fuel for its Safari-I research reactor; and for an 11 month period beginning in 1986 the Y-plant also produced 3.25%-enriched fuel for the Koeberg reactors.

Safari-I is a HEU fueled, light water-cooled, beryllium reflected, swimming pool type research reactor, which achieved first criticality in March 1965. Originally, its design capacity was 6.67 Mw$_t$; however, the test reactor normally operates at 5 Mw$_t$. In 1969 it was upgraded so that the power could be increased to 20 Mw$_t$ for specific requirements. The core, composed of 22-28 fuel elements,[52] has a critical mass of 1.521 kg U-235, and is loaded with 3.604 kg U-235 for 6.67 Mw$_t$ operations, and 3.357 kg for operating at 20 Mw$_t$ (fully Be reflected). The United States supplied it with 87.8 kg of 93%-enriched uranium equivalent (81.6 kg U-235) between 1965 and November 1975.[53] As noted above, Safari-I's power level was cut back to 5 Mw$_t$ in 1977, and in 1981 South Africa announced it was producing 45%-enriched material for Safari-I, and it supplied all of Safari-I's fuel requirements thereafter.

For operating at 5 Mw$_t$, we estimate the annual fuel requirements are about one core, or 3.6 kg U-235/y;[54] while operating at 20 Mw$_t$ would require about 11 kg U-235/y.[55] This suggests that between 1969 and 1981, Safari-I could have operated at 20 Mw$_t$, or there about, for about four years, cumulatively, without running out of United States supplied fuel. Assuming 80 kg of 45%-enriched fuel--an additional ten years supply for 5 Mw$_t$ operation of Safari-I--were produced by the Y-plant after 1981, 6113 kg SWU and 13,975 kg of natural uranium feed would have been

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[50] After start-up, the plant operated 114.5 ± 2.5 mo. Therefore, the two start-up periods represent (4.5 ±2.5)100/[(114.5±2.5)+(4.5±2.5)] = 4±2 percent of the time. Four percent of the tails, ((370,643 kg)(0.04)=14,826 kg), rounds to 15,000 kg.

[51] The production of 1016 kg of 90%-enriched product from natural uranium feed, leaves 355,643 kg of 0.456%-enriched tails = 370,642 kg total - 15,000 kg associated with start-ups.

[52] The core is in the form of a 9x8 grid. In 1963 its design was reported as having 22 fuel elements, 5 control rods, 22 beryllium reflectors and 23 aluminum filler pieces; "Research Reactors," International Atomic Energy Agency, date of information on Safari-I: 1963. In 1990 it was reported as having 28 fuel elements and six control rods; "One-Stop Irradiation Services from the Safari Material Test Reactor, Pelindaba, South Africa" Atomic Energy Corporation of South Africa, Limited, 1990.

[53] Leonard S. Spector, *Nuclear Proliferation Today*, (New York: Vintage Books, A Division of Random House, 1984, p.281.

[54] We assume a capacity factor of 0.65, a fuel burnup of 40 percent, and 1.23 g U-235 consumed/Mwd, thus, (365 d/y)(0.65)(5 Mw)(1.23 g/Mwd)/[(3,604 g/core)(0.4)] = 1.0 cores/y = 3.6 kg/y.

[55] We assume a lower capacity factor of 0.5 due to the additional refuelings, thus, (365 d/y)(0.5)(20 Mw)(1.23 g/Mwd)/[(3,357 g/core)(0.4)] = 3.34 cores/y = 11.2 kg/y.

required, leaving 13,895 kg of 0.456%-enriched tails.[56] Attaching a 30% uncertainty to this estimate, we assume 14,000 ± 4200 kg of tails are associated with the production of Safari-I fuel.

Subtracting the 15,000 ± 7500 kg of tails associated with in-plant inventory production, and 14,000 ± 4200 kg associated with production of Safari-I fuel, from the 370,643 kg total leave 341,643 ± 8600 kg of tails that are assumed to have been generated by the production of HEU for weapons and LEU for the Koeberg reactors.

Koeberg units 1 and 2, light water power reactors each with a design capacity of 922 Mw_e, started up in 1984 and November 1985, respectively. The core inventory or each reactor is 72 t of LEU, enriched to 3.25% U-235. An annual fuel reload for each reactor is 24 t. To fuel these reactors, South Africa purchased 130 t of 3.25%-enriched LEU from Belgium, and another 130 t from Switzerland. The Belgium and Swiss origin fuel would have been sufficient for the two initial cores and 4.8 annual reloads. An additional 60 t of LEU may have been purchased subsequently from China.[57]

Each tonne of 3.25%-enriched LEU requires 10,957 kg of natural uranium feed, 2962 kg SWU, and leave 9957 kg of 0.456% tails.[58] Alternatively, one tonne of 3.25%-enriched fuel could be produced by blending 28.4 kg of 90%-enriched material with natural uranium, or 31.2 kg of 90%-enriched material with depleted uranium (0.456% U-235). In either case, it is clear that in the 11 months the Y-plant produced LEU for the Koeberg reactor fuel, it did not produce anything close to one annual fuel reload.

In Table 1, we estimate the amount of 90%-enriched HEU product as a function of f, the fraction of the total Y-plant separative work devoted to the production of 3.25%-enriched fuel for the Koeberg reactors. Since the Y-plant produced HEU only for about 101-106 months and produced LEU for about 11 months, about 9.6 ± 0.2 percent of the separative work expended for the two products appears to have been devoted to LEU production. Thus, from Table 1, about 838 ± 22 kg of HEU (755 ± 20 kg U-235) is estimated to have been produced.[59] As before, if the U-235 inventory discrepancy is 88 to 105 kg, equivalent to 97 to 117 kg of 90%-enriched HEU, then the quantity of HEU the South Africans presumably reported to the IAEA as being on hand is estimated to be 731 ± 24 kg (659 ± 22 kg U-235).

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[56] If Safari-I had operated with 90%-enriched fuel, only one-half the amount of product, 55 kg, would have been required. This would have required approximately the same SWUs, feed, and tails--8,839 kg SWU, 19,296 kg of feed, and 19,258 kg of 0.456%-enriched tails, and therefore does not affect our calculations. Some of the Y-plant's 90%-enriched product may have been produced to supply future Safari-I fuel requirements. Since it would be fungible with the HEU allocated for weapons, we draw no distinction. Some of the HEU from the now dismantled weapons also may be reserved for Safari fuel.

[57] Mark Hibbs, *Nuclear Fuel*, July 25, 1988 reported that a West German middleman arranged for the export from China to South Africa of 30 t of 3%-enriched uranium and 30 t of 2.7%-enriched uranium in the form of UF_6; Albright, Berkhout, and Walker, *World Inventory of Plutonium and Highly Enriched Uranium 1992*, p. 189.

[58] For $X_P = 0.325$, $X_F = 0.00711$, and $X_T = 0.00456$, the ratio of feed to product (F/P) = 10.96, and the ratio of separative work to product (SWU/P) = 2.96.

[59] The uncertainty also takes into account the 2.5% uncertainty in the quantity of tails associated with production of the HEU for weapons and LEU fuel for the Koeberg reactors.

The Inventory Difference:

The South African AEC estimated of the relative uncertainty (one standard deviation) in the tails assay is 15.6 percent.[60] This, already large error in the tails assay, produces a corresponding relative uncertainty in the calculated inventory of HEU product that is about twice as large--about 35 percent.[61] The 95 percent confidence limits (two standard deviations) in the calculated HEU product inventory is double again, ± 70 percent. In other words, in calculating the inventory of HEU that should be on hand, in order to compare it with what is actually on hand, at best we can only say that there should be about 755 ± 526 kg of U-235 in the HEU. The uncertainty is more than two-thirds the best estimate.

Presumably the South African government reported to the IAEA the amount of U-235 in the HEU product that they had on hand. We estimate that this was was about 659 kg of U-235. Clearly, a more accurate measurement of the tails assay would reduce the 526 kg uncertainty in the calculated amount, and therefore would provide additional useful information to assess South African AEC's claims that what they have is all that was produced; and that the difference between the two figures, 755 kg and 659 kg, is "in the tails." The South African AEC is implying, of course, that a more careful analysis of the tails will lead to a higher tails assay and a best estimate of the HEU inventory closer to what is reported to be on-hand, with a smaller uncertainty in the estimate. But from a purely statistical standpoint, reducing the 15.6% uncertainty in the average tails assay, and therefore the 526 kg uncertainty in the calculated U-235 inventory, could result in an average tails assay that is higher, or lower, and a U-235 inventory that is lower, or higher; and therefore the "actual discrepancy" in the U-235 inventory could just as readily increase, as decrease. To date, only South Africa knows for sure whether the U-235 inventory difference is "in the tails," or whether additional HEU was hidden away.

Conclusion:

Had the Y-plant produced only HEU for weapons, it could have produced about 1000 kg of 90%-enriched uranium (900 kg of U-235). We estimate that some 6000 SWUs were used to produce HEU fuel for the Safari-I reactor--about 80 kg of 45%-enriched fuel, or perhaps about half that amount of 90%-enriched material; another 13,700 to 15,000 SWUs were used to produce 4.6 t to 5.0 t of 3.25%-enriched fuel for the Koeberg reactors. The remaining separative work, 131,000 to 139,000 SWUs, was devoted to HEU production. We estimate that South Africa has on hand 731 ± 24 kg of 90%-enriched uranium. There is an additional inventory discrepancy of 88 to 105 kg U-235 that the South African government claims is actually in the tails.

Little Boy, the gun assembly device dropped on Hiroshima by the United States, was constructed with using about 50 kg of HEU enriched to about 80% U-235 (about 2.5 critical

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[60] 0.00071/0.00456 = 0.1557, where 0.0071 is the one standard deviation uncertainty (the square root of the variance), and 0.00456 is the best estimate of the tails assay.

[61] Found by plugging data from Table 1, into equation (7).

masses), and had yield estimated from 12 to 15 kt.[62] The estimated yield range of the South African weapons is reported to have been 10 to 18 kt.[63] We do not know the relative effectiveness of the neutron reflector in the South African design compared to that used in *Little Boy*. Consequently, we assume as much as 60 kg of 90%-enriched uranium may have been required for each of the six gun assembly type weapons South Africa built, and the seventh that was never completed. There was sufficient HEU production for an additional five weapons of similar design. In addition, the inventory difference, or material unaccounted for, represents another two nuclear weapons worth. This inventory difference could be "in the tails," as claimed by the South African government--the tails were never accurately assayed--or it could be somewhere else.

At the time the nuclear weapons program was dismantled, Armscor experts were apparently working on more sophisticated implosion type weapons.[64] Assuming they could have achieved 2-fold compression of the fissile material with a moderate reflector, only 12.5 kg of U-235 would be required to construct an implosion weapon with a 20 kt yield.[65] Armscor eventually would have been able to construct an arsenal of some 50 nuclear weapons from 731 kg of HEU on hand.

The South African government should be applauded for dismantling its nuclear program and joining the NPT. To resolve any lingering questions about the disposition of its weapon material, it is in everyone's interest, including South Africa's, to have the IAEA, or the United States, take up South Africa's offer to make a more accurate measurement of the enrichment tails assay to determine whether the inventory discrepancy can be reduced.

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[62] Thomas B. Cochran, William M. Arkin, and Milton H. Hoenig, *Nuclear Weapons Databook, Volume I: U.S. Forces and Capabilities*, (Cambridge, MA: Ballinger Publishing Company, 1984), p.32.

[63] *The Arms Control Reporter*, May 1993, p. 455.B.78.

[64] *The Arms Control Reporter*, May 1993, p. 455.B.82.

[65] See Christopher E. Paine and Thomas B Cochran, "Strengthening International Controls on Military Applications of Nuclear Energy," Chapter 9 in *Controlling the Atom in the 21st Century*, edited by David P. O'Very, Christopher E Paine, and Dan W. Reicher, (Boulder: Westview Press, in press, 1993).

TABLE 1
Range of HEU and LEU production levels at the South African Y-plant, assuming 90% enriched HEU and 3.25% enriched LEU

f	HEU			LEU			Feed	SWU
SWU_{LEU}/SWU_{TOTAL}	Total (kg)	U-235 (kg)	SWUs (kg)	Total (kg)	U-23 (kg)	SWUs (kg)	(kg)	Total (kg)
0.000	976	878	156,806	0	0	0	342,619	156,806
0.050	902	812	145,030	2,577	84	7,633	345,122	152,664
0.094	841	757	135,171	4,734	154	14,024	347,218	149,195
0.096	838	755	134,734	4,830	157	14,308	347,311	149,042
0.098	836	752	134,297	4,925	160	14,591	347,404	148,888
0.150	767	690	123,253	7,342	239	21,750	349,752	145,003
0.200	704	634	113,163	9,550	310	28,291	351,897	141,454

Assumptions:
X_F = 0.00711 (feed assay)
X_T = 0.00456 (tails assay)
X_H = 0.9 (HEU assay)
X_L = 0.0325 (LEU assay)
T = 341,643 kg (tails)