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Highly Enriched Uranium Production for South African Nuclear Weapons

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We estimate that South Africa produced 735 ± 53 kilograms of the equivalent of 90 percent-highly enriched uranium (HEU). This amount, were it enriched to 80 to 90 percent, 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. The excess HEU was apparently less enriched than that desired by South Africa for its weapons, but probably still weapons-usable. Implosion-type devices were apparently being researched at the time the nuclear weapons program was dismantled in 1989. Had this effort continued, eventually South Africa would have been able to construct four times as many weapons from the same amount of fissile material. Because of a 15.6 percent uncertainty in the tails assay, the two standard deviation uncertainty in the amount of U-235 in the HEU produced is 256 kilograms. It is in the interest of all parties to reduce this uncertainty.

INTRODUCTION

South Africa decided to build a nuclear weapons program in 1974. The first of six gun assembly-type nuclear weapons was constructed using South African-produced highly enriched uranium. In 1989, South Africa decided to accede to the Treaty on the Non-Proliferation of Nuclear Weapons (NPT) and dismantle its nuclear weapons program. South African officials have since revealed to the International Atomic Energy Agency (IAEA) extensive data on its enrichment plant operations, but they have maintained it is not in the interest of non-proliferation to publicly reveal the amount of HEU produced or on-hand, because it is stored in a single location. As South Africa has already revealed 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. But it is more

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a. Natural Resources Defense Council, Inc., Washington DC.

important to develop a thorough understanding of the material accounting discrepancies. In this paper we estimate how much weapon material was produced, beginning with a brief review of the history of the South African nuclear program.

HISTORY OF SOUTH AFRICA'S NUCLEAR PROGRAM[1]

South Africa's involvement in the nuclear arena began in 1944 when the British government asked South Africa to survey its uranium deposits. The Atomic Energy Board was established in 1948 by Act of Parliament to control the production and sale of uranium, mainly to the Combined Development Agency, the purchasing organization established by the United States and Britain to secure uranium for their nuclear weapons programs.[2] With extensive uranium resources, South Africa was operating 19 mines and 12 extraction plants by 1955. 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" 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 a uranium enrichment capability.[5] The power reactor project was terminated after a short time because of a lack of resources.[5] Under the 1957 nuclear cooperation 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 the Pelindaba site near Pretoria, 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. It was also under IAEA safeguards. The United States supplied it with 606 kilograms of two percent-enriched uranium before it was decommissioned.[6]

Desiring to add value to their uranium export product, the formal decision to start the enrichment project was made in secret in 1967.[5] 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.[7] In 1970 the state-controlled Uranium Enrichment Corporation (UCOR) was established to build the enrichment plant at the Valindaba site adjacent to Pelindaba;[5] 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.[8] Construction of the Pilot Enrichment Plant (the Y-plant), based on the gas-nozzle technology, commenced in 1971.

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.[9]

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.[10] Building 5000 at Pelindaba was probably the site of early nuclear weapons manufacture.[11] Approval was given for a nuclear test site in the Kalahari desert in 1974, and the first stages at the lower end of the cascade of the Y-plant were commissioned by the end of the year.[12] 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 suspended Safari-I fuel exports in early 1975. The last export of U.S. fuel was in November 1975. By 1977, the Safari-I power level was reduced from 20 to 5 MW_t in order to conserve fuel.[5] In 1975, 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.[13] By 1978, however, a decision was made to build a smaller facility, said to be capable of producing 75 metric tonnes 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.[14] In 1979, South Africa announced the successful development of 45 percent-enriched fuel for the Safari-I reactor. From that point onward South Africa supplied its own fuel for Safari-I.[5]

Three shafts were drilled at the Kalahari test site to a depth of 180 to 200 meters for demonstration. One shaft was abandoned due to geological conditions. The other two were completed in 1977.[15] On 6 August 1977 the Soviet Union alerted the United States to the construction activities at the Kalahari test site. Extensive pressure from the superpowers—the United States, France, Great Britain, and West Germany—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.[5]

In March 1977, the Y-plant operated as a full cascade for the first time;[5] and the first relatively small quantities of HEU were withdrawn in January 1978.[16] Toward the end of 1978, sufficient HEU had been produced to be converted into metal, molded and machined into weapon parts, and fitted into the first nuclear weapon.[5] The uranium was relatively impure and enriched only to about 80 percent in the isotope U-235. The uranium was later removed and recycled through the enrichment plant to clean it up and upgrade the enrichment.[5] In 1979 a decision was made by the head of government that Armscor, the state-owned arms manufacturer, should produce the nuclear devices, and that the role of the AEC would be limited to uranium enrichment and some neutron physics calculations.[5] The second nuclear weapon was provided with HEU in the same year.[5] Advena (the secret Armscor facility at Kentron Circle, 25 kilometers west of Pretoria, where most of the subsequent weapons work took place) was commissioned in 1980 and completed the following year.[5] In 1985 the government decided to limit the size of its nuclear arsenal to seven nuclear weapons.[5]

An accident in August 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 until April 1980, when it resumed operations.[2] HEU withdrawal commenced in July. In this same year, South Africa announced the successful development of 45 percent-enriched fuel for the Safari-I reactor. From that point onward South Africa supplied its own fuel for Safari-I.[5]

All South African HEU was produced in the Y-plant. Construction of the second enrichment plant—the semi-commercial Z-plant—began in 1979. It was commissioned in 1984, and produced its first LEU in August 1988.[5] 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 five percent U-235.[17] As of the end of 1991, the plant could operate at its optimum production of 300,000 kilograms SWU per year.[18] 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.

During the period June to December 1986, the Y-plant was reconfigured to produce 3.25 percent-enriched uranium for the first four Lead Test Assemblies for the twin 922 MW_e Koeberg reactors.[5] Thereafter, it produced HEU until it ceased operating on 1 February 1990.[2]

In September 1989, just after taking office, President Frederik W. de Klerk ordered the nuclear weapons program to be terminated. Plans were drawn up, and on 26 February 1990, President de Klerk provided written instructions to start the dismantlement process.[5] 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, and neutralize the Armscor facility before acceding to the NPT.[5] As noted above, the Y-plant ceased operations on 1 Feb-

BOX 1: Key Milestones in the Operation of the Y-plant

1971	Construction begins.
1974	First stages of the lower end of the cascade were commissioned by the end of the year.
1977	First full operation of the entire plant in March.
1978	First production of HEU in January and sufficient 80 percent-enriched HEU for the first nuclear weapon by the end of the year.
1979	Production stopped in August.
1980	Production resumed in April.
1981	HEU withdrawal resumed in July.
1986	Y-plant reconfigured and used from June to December to produce LEU (3.25 percent-enriched fuel for the Koeberg reactors).
1990	Plant ceased production on 1 February.

ruary 1990.[5] In early July 1991, the last weapon was dismantled. The Armscor facility was decontaminated and returned to the AEC and switched to making medical equipment.[5] South Africa acceded to the NPT on 10 July 1991, signed a Comprehensive Safeguards Agreement with the IAEA on 16 September 1991, and provided IAEA with an inventory of nuclear materials and facilities on 30 October 1991.

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.[19]

During its 15 year operating history (end of 1974 to 1 February 1990) the Y-Plant was still being completed during the first 27 months of operation (end of 1974 to March 1977); was reaching equilibrium without producing HEU during two periods totaling 25 months (March 1977 to January 1978 and April 1980 to July 1981); was producing LEU for six months (June to December 1986); was shut down for eight months (August 1979 to April 1980); and was producing HEU for 115.5 months (January 1978 to August 1979, July 1981 to June 1986, and December 1986 to 1 February 1990). During the first 10 months, or so, of HEU production, the production rate was low; and in the early 1980 a small portion of the HEU production was used for Safari reactor fuel.

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 assay ($\sigma[X_T]$), and the calculated two standard deviation uncertainty in the estimate of the amount of U-235 in the HEU ($2\sigma[X_H H]$):[20]

X_F = 0.00711 (i.e., 0.711 percent U-235)

$X_T \pm \sigma[X_T]$ = 0.00456 ± 0.00071

$2\sigma[X_H H]$ = 526 kilograms.

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 percent to 0.6 percent 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 equation (1) into equation (2), and solving for $X_H H$ gives:

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

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

$$X_H H = X_H \frac{(X_F - X_T)\, T_H}{(X_H - X_F)} \tag{4}$$

The uncertainty in $X_H H$, $\sigma[X_H H]$, is approximated by applying to equation (3) the general relationship:[21]

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

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

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

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

$$\frac{\sigma[X_H H]}{X_H H} \approx \frac{\sigma[X_T]\, T}{(X_F - X_T)\, T_H} \tag{7}$$

which can be rewritten as:

$$X_H H \approx \frac{\sigma[X_H H]}{\sigma[X_T]} (X_F - X_T) \frac{T_H}{T} \tag{8}$$

An upper limit on the amount of U-235 in the HEU product can be found by setting $T_H = T$, giving $X_H H$ less than 945 kilograms. Later we will be able to show that $T_H / T = 0.796$, in which case $X_H H \approx 752 \pm 256$ kilograms.

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., $2\sigma[X_H H] = 526$ kilograms, was over five times the "actual discrepancy."[22] This would not be an issue unless the amount of HEU that 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 discrepancy; and its magnitude is less than 105 kilograms (= 526 / 5), and probably greater than 88 kilograms (= 526/6).[23] 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 647 and 664 kilograms.

We do not know the average value of X_H, and in fact all of the HEU is not of the same U-235 assay. Nevertheless, we can convert the results into 90 percent U-235 equivalence, in which case we can say that South Africa enriched HEU equivalent to the production of 719 to 738 kilograms of 90 percent-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 kilograms; 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:

$$
\begin{aligned}
T &\approx \frac{(\sigma\,[X_H H]\,)\,1-\dfrac{X_F}{X_H}}{\sigma\,[X_T]} \qquad (9)\\
&\approx 367{,}000 \text{ kilograms}
\end{aligned}
$$

which agrees well with the 370,643 kilogram 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 period of equivalent production lost during the approach to steady state.[24] The equilibrium time for tails withdrawal, t_T, is similarly defined. The difference in these two times, $(t_P - t_T)$, multiplied by 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.[25]

Their approximation for t_P is:

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

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 $f(X_F, X_P)$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, $(1 - \alpha) = 0.003$.[26] Unfortunately, we do not know h 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.

Based on the operating history, reported above, the Y-plant's initial start-up time was 10 months (March 1977 to January 1978), and the second start-up period—following the 1979 accident and repairs—was 15 months (April 1980 to July 1981). But we do not know what fraction of each period was associated with getting the bugs out of the system, and what fraction represents the effective start-up time. Also, following the 1979 accident, 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 may not have been recycled. Lacking better information, we assume the effective start-up time was 7 ± 3 months. The combined 14 ± 6 months represents about 10 percent time during which tails were withdrawn. We therefore assume 37,000 ± 16,000 kilograms of tails were associated with production of in-plant inventory during which there was no product produced.

Had the Y-plant been devoted entirely to HEU production, after start-up it could have produced about 950 ± 50 kilograms of 90 percent-enriched uranium.[27]

Fueling Safari-I and the Koeberg Reactors

Safari-I is an 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 five 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 to 28 fuel elements,[28] has a critical mass of 1.521 kilograms U-235, and is loaded with 3.604 kilograms U-235 for 6.67 MW_t operation, and 3.357 kilograms for operating at 20 MW_t (fully beryllium-reflected). The United States supplied it with 87.8 kilograms of 93 percent-enriched uranium equivalent (81.6 kilograms U-235) between 1965 and November 1975.[6] As noted above, Safari-I's power level was cut back to five MW_t in 1977, and in 1981 South Africa announced it was producing 45 percent-enriched material for Safari-I, and it supplied all of Safari-I's fuel requirements thereafter.

For operating at five MW_t, we estimate the annual fuel requirements are about one core, or 3.6 kilograms U-235 per year;[29] while operating at 20 MW_t would require about 11 kilograms U-235 per year.[30] This suggests that between 1969 and 1981, Safari-I could have operated at roughly 20 MW_t for about four years, cumulatively, without running out of United States supplied fuel. Assuming 80 kilograms of 45 percent-enriched fuel—an additional 10 year supply for five MW_t operation of Safari-I—were produced by the Y-plant after 1981, 6,113 kilograms SWU and 13,975 kilograms of natural uranium feed would have been required, leaving 13,895 kilograms of 0.456 percent-enriched tails.[31] Attaching a 30 percent uncertainty to this estimate, we assume 14,000 ± 4,200 kilograms of tails are associated with the production of Safari-I fuel.

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 tonnes of LEU, enriched to 3.25 percent U-235. An annual fuel reload for each reactor is 24 tonnes. To fuel these reactors, South Africa purchased 130 tonnes of 3.25 percent-enriched LEU from Belgium, and another 130 tonnes from Switzerland. The Belgian and Swiss origin fuel would have been sufficient for the two initial cores and 4.8 annual reloads. An additional 60 tonnes of LEU may have been purchased subsequently from China.[32]

Each tonne of 3.25 percent-enriched LEU requires 10,957 kilograms of natural uranium feed, 2,962 kilograms SWU, and leave 9,957 kilograms of 0.456 percent tails.[33] Alternatively, one tonne of 3.25 percent-enriched fuel could be produced by blending 28.4 kilograms of 90 percent-enriched material with natural uranium, or 31.2 kilograms of 90 percent-enriched material with depleted uranium (0.456 percent U-235). In either case, it is clear that in the six months the Y-plant produced LEU for the Koeberg reactor fuel, it did not produce anything close to one annual fuel reload. Assuming 0.5 tonnes of fuel per assembly, the fuel requirements for the four Lead Test Assemblies would have been approximately two tonnes.

In table 1, we estimate the 90 percent-enriched HEU equivalent product available for weapons; the amount of 45 percent-enriched product for fueling the Safari-I reactor; and the amount of 3.25 percent-enriched product for the Koeberg reactors that were produced by the Y-plant. We have assumed that the SWU production for each was in proportion to the operating time during which each product was produced—109.7 months (90.6 percent of the time) for the production of HEU for weapons; 5.3 months (4.4 percent of the time) for

Table 1: Estimated Y-plant production of 90 percent-enriched HEU for weapons; 45 percent-enriched HEU for Safari-I; and 3.25 percent-enriched for LEU for the Koeberg reactors.

	Total *kg*	U-235 *kg*	SWU *kg*	Feed *kg*	Tails *kg*
HEU (90% U-235)	843	758	133,415	295,880	295,038
HEU (45% U-235)	80	36	6,113	13,975	13,895
LEU (3.25% U-235)	2,482	81	7,352	27,193	24,711
Total	**3,404**	**875**	**148,880**	**337,047**	**333,644**

Safari-I fuel production; and six months (5.0 percent of the time) for Koeberg reactor fuel production.

Thus, from table 1, about 843 ± 52 kilograms of HEU (758 ± 47 kilograms U-235) is estimated to have been produced.[34] As before, if the U-235 inventory discrepancy is 88 to 105 kilograms, equivalent to 97 to 117 kilograms of 90 percent-enriched HEU, then the quantity of HEU the South Africans presumably reported to the IAEA as being on hand is estimated to be 735 ± 53 kilograms (662 ± 49 kilograms U-235).

THE INVENTORY DIFFERENCE

The South African AEC estimated of the relative uncertainty (one standard deviation) in the tails assay is 15.6 percent.[35] 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.[36] 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 758 ± 526 kilograms of U-235 in the HEU. The uncertainty is more than two thirds of 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 about 662 kilograms of U-235. Clearly, a more accurate measurement of the tails assay would reduce the 526 kilogram 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—758 kilograms and 662 kilograms—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 percent uncertainty in the average tails assay, and therefore the 526 kilogram 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 950 kilograms of 90 percent-enriched uranium (860 kilograms of U-235). We estimate that some 6,100 SWUs were used to produce HEU fuel for the Safari-I reactor—about 80 kilograms of 45 percent-enriched fuel; another 7,400 SWUs were used to produce 2.5 tonnes of 3.25 percent-enriched fuel for the Koeberg reactors. The remaining separative work—135,000 SWUs—was devoted to HEU production. We estimate that South Africa had on hand HEU equivalent to 735 ± 53 kilograms of 90 percent-enriched uranium. There is an additional inventory discrepancy of 88 to 105 kilograms 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 kilograms of HEU enriched to about 80 percent U-235 (about 2.5 critical masses), and had yield estimated from 12 to 15 kilotons.[37] The estimated yield range of the South African weapons is reported to have been 10 to 18 kilotons.[38] 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 kilograms of 90 percent-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. The South African AEC claims that there was barely enough HEU for the six weapons. Consequently, the excess HEU was probably less than the desired enrichment, but probably still weapons-usable. 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.

At the time the nuclear weapons program was dismantled, Armscor experts were apparently working on more sophisticated implosion-type weapons.[11] Assuming they could have achieved twofold compression of the fissile material with a moderate reflector, only 12.5 kilograms of U-235 would be required to construct an implosion weapon with a 20 kiloton yield.[39] Assuming all of the HEU available for weapons were brought up to 90 percent-enriched, Armscor eventually would have been able to construct an arsenal of some 50 nuclear weapons from 735 kilograms 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, to reduce the 526 kilogram inventory difference in the U-235 in the HEU product. Perhaps the U.S. should take up South Africa's offer to make a more accurate measurement of the enrichment tails assay.

NOTES AND REFERENCES

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, Colorado: Westview Press, 1990); Leonard S. Spector, *Nuclear Proliferation Today* (New York: Vintage Books, A Division of Random House, 1984); 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. Stumpf, "South Africa's Nuclear Weapons Programme," Atomic Energy Cooperation of South Africa Ltd. 1993.

3. Spector, *Nuclear Proliferation Today*, p. 280.

4. Spector, with Smith, *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 DC, 23 July 1993. Dr. Stumpf is Chief Executive Officer of the Atomic Energy Corporation of South Africa. A transcript of his talk has been released by the South African Embassy.

6. Spector, *Nuclear Proliferation Today*, p. 281.

7. Spector, *Nuclear Proliferation Today*, p. 283.

8. Spector, *Nuclear Proliferation Today*, p. 284.

9. *The Arms Control Reporter*, May 1993, p. 455.B.81.

10. 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).

11. *The Arms Control Reporter*, May 1993, p. 455.B.82.

12. 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 Co., 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).

13. Spector, (*Nuclear Proliferation Today* [New York: Vintage Books, 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 5,000 tons of low-enriched uranium per year." To produce 5,000 tonnes of 3.25 percent-enriched LEU, at a tails assay of 0.3 percent, would require 20 million SWUs, 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 5,000 tons of U_3O_8, then only two million SWUs annually would be required to produce 540 tonnes of 3.25 percent-enriched LEU annually, at 0.3 percent tails.

14. *Ibid.*, and Spector, with Smith, *Nuclear Ambitions*, p. 277.

15. *The Arms Control Reporter*, May 1993, p. 455.B.80.

16. Stumpf, "South Africa's Nuclear Weapons Programme."

17. Stumpf, "South Africa's Limited Nuclear Deterrent Programme." 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.

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

19. Following this point in the paper, 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) through (d) publicly, except for the uncertainty in (d), we will be making our own estimates, (e) through (h), of the South Africa's measurements and best estimates, (a) through (d). Each of our best estimates has a corresponding uncertainty.

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

21. See, for example, Philip R. Bevington, *Data Reduction and Error Analysis for the*

Physical Sciences (New York: McGraw-Hill Book Co., 1969) p. 60.

22. 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.

23. We infer this, since the 526-kilogram figure was not reported as being more than six times the "actual discrepancy." The "actual discrepancy," of course, could be even less than 88 kilograms.

24. Benedict, Pigford, and Levi, *Nuclear Chemical Engineering,* pp. 678–679.

25. *Ibid.*, equation (12.204), p. 681, and equation (12.209), p. 682.

26. *Ibid.*, p. 895.

27. The production of 953 kilograms of 90 percent-enriched product from natural uranium feed, leaves 333,643 kilograms of 0.456 percent-enriched tails = 370,643 kilograms total—37,000 kilograms associated with start-ups.

28. The core is in the form of a 9 × 8 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, information on Safari-I is from 1963. In 1990 it was reported as having 28 fuel elements and 6 control rods; "One-Stop Irradiation Services from the Safari Material Test Reactor, Pelindaba, South Africa," Atomic Energy Corporation of South Africa, Limited, 1990.

29. We assume a capacity factor of 0.65, a fuel burnup of 40 percent, and 1.23 grams U-235 consumed per megawatt-day (MWd^{-1}), thus, (365 days per year) · (0.65) · (5 megawatts) · (1.23 gm MWd^{-1}) / [(3,604 grams per core) · (0.4)] = 1.0 cores per year = 3.6 kilograms per year.

30. We assume a lower capacity factor of 0.5 due to the additional refuelings, thus, (365 days per year) · (0.5) · (20 megawatts) · (1.23 gm MWd^{-1}) / [(3,357 grams per core) · (0.4)] = 3.34 cores per year = 11.2 kilograms per year.

31. If Safari-I had operated with 90 percent-enriched fuel, only one half the amount of product, 40 kilograms, would have been required. This would have required approximately the same SWUs, feed, and tails—6,428 kilograms SWU, 14,046 kilograms of feed, and 14,006 kilograms of 0.456 percent-enriched tails; and therefore does not affect our calculations. Some of the Y-plant's 90 percent-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.

32. Mark Hibbs (*NuclearFuel*, 25 July 1988) reported that a West German middleman arranged for the export from China to South Africa of 30 tonnes of three percent-enriched uranium and 30 tonnes of 2.7 percent-enriched uranium in the form of UF_6; Albright, Berkhout, and Walker, *World Inventory of Plutonium and Highly Enriched Uranium 1992* (Oxford: SIPRI and Oxford University Press, 1993) p. 189.

33. 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.

34. The uncertainty takes into account the ± 16,000 kilogram uncertainty in tails associated with start-up, the ± 4,200 kilogram uncertainty in tails associated with pro-

duction of Safari-I fuel, and the ± 7,400 kilogram uncertainty in the tails associated with production of Koeberg fuel.

35. 0.00071 / 0.00456 = 0.1557, where 0.00071 is the one standard deviation uncertainty (the square root of the variance), and 0.00456 is the best estimate of the tails assay.

36. Found by plugging data from table 1, into equation (7).

37. Thomas B. Cochran, William M. Arkin, and Milton H. Hoenig, *Nuclear Weapons Databook, Volume I: U.S. Forces and Capabilities* (Cambridge, Massachusetts: Ballinger Publishing Co., 1984) p. 32.

38. *The Arms Control Reporter*, May 1993, p. 455.B.78.

39. 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, Colorado: Westview Press, in press).