Chapter 5 Kentron Circle Facility

At the commissioning of the Kentron Circle facility on May 4, 1981, Prime Minister P.W. Botha told the highly secretive and selective crowd: "The time has come when the South African "Plowshare" must be forged into a sword, for the battle that awaits."[1] Circle was to be South Africa's own nuclear weapons research, development, and manufacturing facility dedicated to the creation of nuclear weapon systems. The facility was under the control of the defense establishment, which wanted fully weaponized, deliverable nuclear weapons.

Botha delivered his speech by the new high security vault inside the Circle building, designed to securely store nuclear weapons. According to a senior official present at the commissioning, in front of him was arrayed nuclear weapons components and a prototype mock-up of a warhead for a sophisticated glide bomb under development by Armscor.

Botha likened Circle to Los Alamos and Livermore National Laboratories, centers of US nuclear weapons research and development. In practical terms, however, Circle functioned more like Sandia National Laboratories. It concentrated on refining the parts of the nuclear weapon that are outside the central nuclear core or pit, and ensured warhead reliability, safety, and security.

Botha told the audience that a nuclear weapon is "primarily a political weapons system, not a military system." It is a weapon of "inducement, persuasion, and compulsion in the hands of the leaders of the world," he added. "This political weapon opens a new possibility," namely "the option for the RSA to stipulate its birthright at the negotiating table of the Greats, with nuclear deterrence strategy as its foundation."[2] At the end of his speech, Botha presented a commemorative plaque which reportedly read: "For all South Africans."[3]

Botha was followed by André Buys, Circle's first Plant Manager. Buys' task was to describe all the sensitive items in front of the esteemed audience, which included several cabinet ministers. Off-script for such a momentous occasion, he also raised doubts about whether South Africa's nuclear program had an adequate nuclear strategy. Implicit in his comments was the need for more thorough guidance on the type and number of nuclear weapons that needed to be built and how they would be used in a crisis. Afterwards, at the reception, Buys said that Botha ignored him but F.W. de Klerk, who attended as Minister of Mineral and Energy Affairs, came up to him and said that he liked what Buys had said. Buys was struck with a suspicion that there could be a split at the highest level of government about the nuclear weapons program.

The Circle facility

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[1] Prime Minister P.W. Botha, *Draft Speech for the Opening of Kentron Circle,* May 4, 1981, in Afrikaans. Original in Nic von Wielligh and Lydia von Wielligh-Steyn, *Die Bom* (South Africa: Litera Publikasies, 2014), Appendix, translated by Schreiber Translations, Inc. for Institute for Science and International Security, July 7, 2015.
[2] *Draft Speech for the Opening of Kentron Circle,* op. cit.
[3] Interview with André Buys, July 31, 2002.

Armscor built the Kentron Circle facility utilizing a design by a leader of the AEB PNE team. The Circle facility, located about 15 kilometers east of Pelindaba, essentially duplicated under one roof, most of the development and manufacturing capabilities in the valley below Pelindaba. However, Armscor did not duplicate the AEB's facilities to conduct criticality or dragon experiments. The focus was on making deliverable nuclear weapons utilizing a core developed at the AEB in the late 1970s.

Circle was built in 1980 and occupied in 1981. The facility comprised the Circle building itself, a nearby environmental test facility that was involved in ensuring that nuclear weapons could withstand deployment on aircraft and delivery to the target, and a magazine for storing high explosives and propellants that had been disguised externally to hide its purpose, according to a former senior leader of the nuclear weapons program. Figure 1 shows the Circle complex in a commercial satellite image. Figure 2 shows the Circle building, as it appeared after the program was cancelled. Standing in the main entrance, figure 3 shows a central bay of the building.

Figure 1 Commercial satellite image of the Circle Complex. Visible is the main building, the environmental test building, and a magazine for storing high explosives and propellants.

Figure 2 Main Circle building, with its main entrance visible.

Figure 3 Looking from the main entrance into the central bay of the Circle building in 2002 after building renovations following end of nuclear weapons program. The original personnel portal for the facility is on left.

Circle facility was built deep within Armscor's Gerotek site, which was being built at the same time (see figure 4). This site was designed to test vehicles at high speeds and on various types of road surfaces and grades.

A high priority was maintaining the secrecy of the nuclear weapons program, particularly the existence of the Circle complex. According to a former senior member of the program, officials thought it too risky to build Circle at a nuclear or armaments manufacturing site. They concluded that it must be sited on its own and that it should not be easily accessible to outsiders. Upon reflection, Gerotek seemed like a good choice. If someone asked about the Circle buildings, they could be identified as defense industries workshops. Such a question did arise in fact in the mid-1980s, when an American was in a test vehicle on the high speed track and asked about the Circle building.

Figure 4 The Gerotek site where the Circle facility was located. A high speed test track can be seen in the center of the photo. The Circle facility is on the hillside above the track.

The turn-off to the Circle facility, marked only with a sign that said "Workshop," is several minutes' drive inside Gerotek's main gate. Figure 5 shows the non-descript turnoff to Circle taken in 2002. (The workshop sign had been removed by the time this picture was taken.) The entire site is hilly. On the hillsides can be seen graded tracks for testing military vehicles.

Figure 5 Road inside Gerotek right before the turnoff to the Circle facility (first left). Test tracks can be seen in the distance on the hillside.

Initially, Circle was to be an underground facility. An embankment was constructed around part of the facility, according to a former leader of the program. The satellite image in figure 1 and figure 6 show the berm and how the facility was dug into the hillside. However, this plan was quickly abandoned as too expensive.

Figure 6 Main entrance of the Circle building, as viewed from the top of a berm. Photo credit: Armscor

Nonetheless, the berm remained as the only external clue to the potential importance of the building and blocked prying eyes from seeing the building from a nearby road deep within the Gerotek compound. Figure 7 shows a view of the Circle building from the bridge over the test track; only the top portion is visible.

Figure 7 Top of Circle building visible in the distance from the oval race track at Gerotek

The exterior of the Circle building is nondescript. Advena's managers blocked proposals to place sophisticated communications on the roof to avoid a "signature" that might attract the attention of intelligence agencies.

Armscor imposed a more stringent security regime on the personnel in the program than the AEB had exercised in the 1970s. Circle employees acted as if they could be observed by satellites. Employees going between Circle and Pelindaba took special precautions to prevent anyone from following them or uncleared Pelindaba employees from seeing them enter or leave the road from the military vehicle testing facility.[4]

[4] South Africa's nuclear explosive program in the 1970s was widely known about. In 1984, the CIA wrote: "Evidence that South Africa has developed a significant nuclear explosives capability is substantial and compelling." [Director of Central Intelligence, *Trends in South Africa's Nuclear Security Policies and Programs*, National Intelligence Estimate, October 5, 1984, declassified version]. However, this report recognized that South Africa imposed tighter security over its nuclear explosives program after the 1977 Kalahari incident. In particular, the authors of the report appeared not to know that South Africa had embarked on a program to produce deliverable nuclear weapons, although they recognized correctly that it possibly could have done so. A related issue is when Western intelligence agencies discovered the true purpose of the Circle building. US satellites likely picked up the construction of Circle, but one official said that the US intelligence agencies had misunderstood Circle's true purpose, perhaps for the first five or six years of its operation. Certainly, by 1988 or 1989, the true purpose of Circle was known, he added.

A number of AEB personnel were transferred to Circle along with key manufacturing equipment. According to a leader of the Armscor program, others at the AEB, such as the leader of the PNE program and designer of Circle, remained active in providing technical advice for several years after the transfer of the program to Armscor. Armscor also had to recruit new engineering talent. According to a leader of the Armscor nuclear program, technical capabilities were of critical importance; however, so was recruiting people who were responsible and mild-mannered. He said that they wanted to avoid fanatics.

The AEB remained responsible for supplying highly enriched uranium. It also continued theoretical nuclear weapons work.[5]

The nuclear weapons program's main office was at the Kentron headquarters, near Pretoria and staffed jointly by Armscor and Air Force personnel.[6] It was under high security and access was carefully controlled. To prevent eavesdropping, a wire mesh was put around the office during one weekend when everyone was gone. The purpose of the office was unknown to others in the building; they just knew it was a cover for something. Given the extensive overseas smuggling and other secret activities undertaken by Armscor, the office did not create any undue suspicion in the building.

Inside Circle

Inside the Circle building are two floors with a total of 8,000 square meters of floor space. The lower floor was dedicated to developing and making nuclear devices. Offices and conference rooms were located on the second floor.

The site was designed in particular to carry out further development and routine manufacturing of gun-type nuclear weapons. The building was also capable of conducting research and development of implosion-type nuclear weapons.

The first floor of the Circle building had conventional workshops for making mechanical and electrical equipment for a gun-type weapon; storage rooms; uranium casting and machining workshops for gun-type weapons; a large vault; integration rooms where portions of the devices were assembled; and eight thick-walled "cells" for testing internal ballistics, propellants, igniters, and small quantities of high explosives for self-destruct mechanisms. An explosive test chamber located in one of the cells could handle up to 2.5 kilograms of high explosive. It was used to conduct many plane-wave high explosive tests and detonator experiments with shaped charges related to implosion designs and to develop high-speed instrumentation necessary for developing these designs. Another cell contained the "pig sty," a wooden enclosure where projectile tests were done for the gun-type device.

In anticipation of an accident with high explosives, which in the worst case risked blowing off the roof and exposing the facility, the designers put a "plenum" or large room above the high

[5] Johann Viljoen and Deon Smith, *The Birth, Life, and Death of South Africa's Nuclear Weapons Program*, Manuscript commissioned by the Institute for Science and International Security, 1999, unpublished.
[6] Hannes Steyn, Richardt van der Walt, and Jan van Loggerenberg, *Armament and Disarmament: South Africa's Nuclear Weapons Experience* (Pretoria: Network Publishers, 2003), p. 75.

explosive cells on the second floor. In an accident, this room would serve to dissipate the overpressure from an explosion, preventing the collapse of the roof or the walls. Holes at one end of the room would allow the explosion to vent. From the outside, the holes were disguised as ventilation ducts (see figure 8).

Figure 8 Fake ventilation ducts (left) hid holes in the walls of the second story plenum (right photo at back; light can be seen through these holes) designed to minimize damage in an accidental explosion in internal high explosive test cell. The holes would have served to dissipate any overpressure from an accident in an indoors high explosive facility. In photo on right, one of the orange blast covers over an explosive cell has been removed. These blast covers are secured by special bolts that are designed to break in an explosion and also reduce the destructive force of an accidental blast.

In the early 1980s, the program employed about 100 people, of which only about 40 were directly involved in the weapons program. Only 20 actually built the devices. The rest were involved in administrative support and security. Figure 9 shows Circle's organizational structure. By the time the program was canceled in 1989, the work force had risen to 300, with about half directly involved in weapons work.

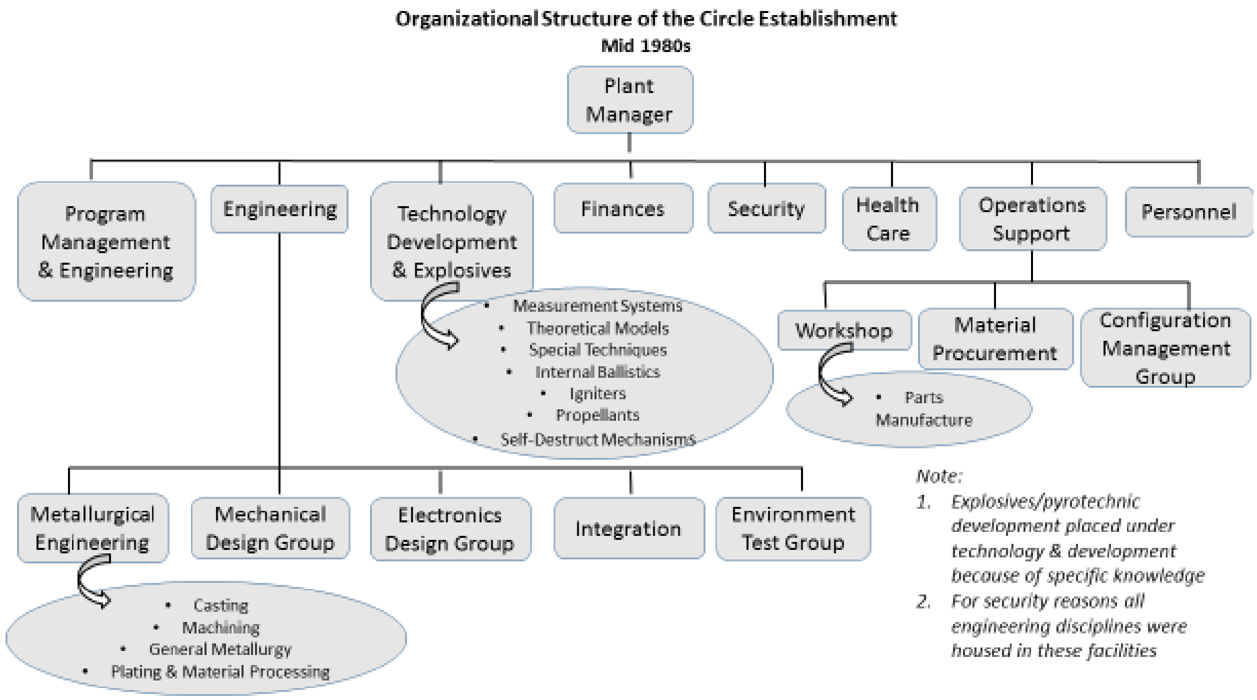

Figure 9 Organizational structure of the Circle facility. Source: Armscor

The Armscor approach

Armscor approached the problem of building nuclear weapons very differently than the AEB, which was reorganized as the Atomic Energy Corporation (AEC) in 1982. Comprised principally of engineers and employed by the military, Armscor's philosophy differed from that of the AEC, which was essentially a civilian scientific organization.

Armscor considered the AEB's November 1979 device to be an unqualified design that could not meet the rigid safety, security, and reliability specifications then under development by Circle engineers. Moreover, the first device was not deliverable.

The AEB device was transferred to Circle. Prior to the move, it had been temporarily stored in an abandoned coal mine at Witbank, a former military ammunitions depot. Armscor modified the device slightly, including re-plating the metal HEU components in 1982, according to South Africa's declaration to the IAEA. The device was renamed Melba, and it lacked many of the safety measures of later devices.

Armscor implemented a capability to conduct a nuclear explosive test more rapidly than the period of time required for the 1977 test. It developed methods for quickly transporting the device to the Kalahari test site and placing it down the hole. The latter involved special trucks with winch equipment rather than stationary equipment of the type used in 1977. Necessary equipment was kept ready at the Circle complex. According to an Armscor official, even the explosive yield would have been estimated only through seismic methods. Instrumentation would mainly be limited to that necessary for assessing any radioactive fallout risks to the public from the possible accidental release of material during the explosion. Although speed was desired, the time required to prepare the Melba test device and conduct a test would likely have been measured in days. Although a 24 hour deployment was the goal, Armscor officials cast doubt on its ability to test so quickly.

To establish an initial credible deterrent, Armscor manufactured its first device in 1981 and 1982, which it considered a "pre-qualification" model. The HEU components had been made at the AEC, however. The yield was six kilotons, implying that, like Melba, it contained 80 percent HEU.[7] According to an Armscor official, it was capable of being dropped from a plane. This device gave South Africa a way to carry out its initial nuclear strategy, which required deliverability, albeit primitive at this stage. It was initially named Hobo, but later renamed Cabot.

Armscor's goal was to produce warheads for delivery by stand-off weapons launched from Buccaneer bombers. The stand-off weapon was the video-controlled Raptor, or H2, glide bomb with flip-out wings (figures 10 and 11). This highly accurate weapon was developed as a smart weapon for conventional use at the Kentron facility at Irene, Pretoria. The range was about 60 kilometers, and it could be delivered with one meter accuracy.

In a nuclear mode, one or two Raptors would be mounted on the innermost pilings under the Buccaneer's wing. The two outer pilings were for a control pod for the weapon and an anti-electronic warfare pod.

Figure 10 South Africa's 1980s nuclear delivery system, the Raptor 1, or H2, Glide Bomb with inertial and optical guidance.

[7] *Kramat Capability: Current Status and Further Development*, part of September 3 1987 submission to the Witvlei Control Committee (WBK), in Afrikaans. Original in *Die Bom*, op. cit. See also their English version, namely *The Bomb* (Pretoria: Litera Publications, 2015), Appendix.

Figure 11 Buccaneer with the non-nuclear Raptor 1 (H2) on the inner pylons (wings folded in). The H2-Comms Pod is on the starboard outer pylon and an ECM pod is on the port outer pylon. In nuclear strike mode, the outer pylons would have a control pod for the nuclear weapons and an electronic warfare pod.

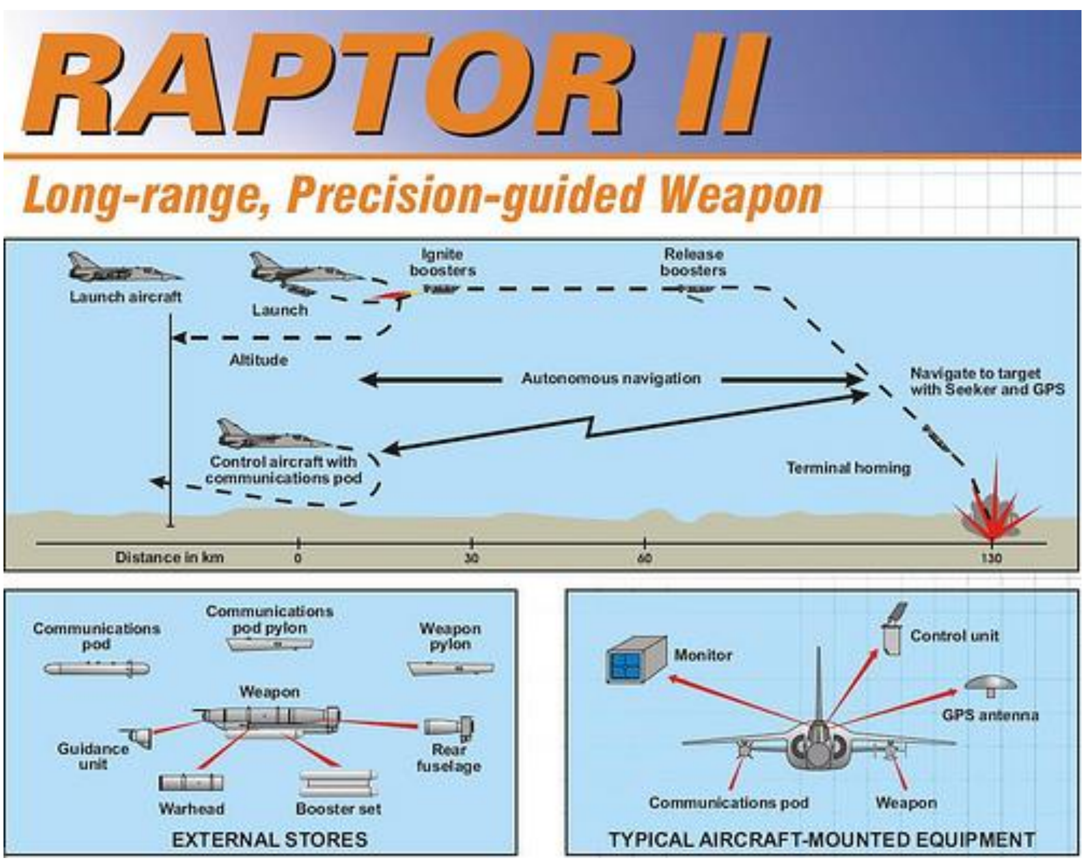

Figure 12 Raptor II firing procedure, which is more advanced than Raptor 1 but similar, showing how glide bomb is delivered to a target.

After firing a Raptor, the aircraft pilot and navigator would continuously communicate with the warhead (figure 12). The Raptor would travel to the target and then dive in its final approach. A height sensor would detonate the warhead above ground as an airburst to reduce the amount of radioactive fallout. However, the warhead was not armed when it started its dive. The pilot had to send a signal to arm the device before the pre-determined height of detonation was reached. If no signal were received by then, the warhead would self-destruct.

Key to Armscor's development of nuclear weapons was reliability, safety, and security.[8] The system engineering department at Circle developed very strict qualification specifications. In addition, extraordinary secrecy requirements forced Circle to make many items in-house. As a result, according to Armscor, design refinement and re-qualification of the hardware took several years.

Many difficulties were encountered in the early years at Circle. Some of the development and production problems concerned the density of the neutron reflectors and the plating of uranium components with nickel. The latter was solved only after trying many approaches. The neutron reflector was made using tungsten-copper, and many problems were confronted in building this part, which required a high density. Density affects the explosive yield of a nuclear device, according to a former senior official close to the IAEA knowledgeable about the South African program. In addition, much effort was invested in the reliability of arming and safing devices.

Ultimately, however, Armscor's production models were highly reliable – they had redundancy built into the system whenever possible, and they were thoroughly qualified in terms of their internal ballistics and mechanical arming and safing operations.

Each nuclear device was divided into two sections, a front and back. With the HEU distributed between the two halves in subcritical quantities, the design minimized the possibility of accidental detonation or unauthorized use. Both halves had to be assembled together to have a nuclear explosion. In essence, the separation of the halves was South Africa's key control philosophy.

The front end contained the bulk of the HEU, the neutron tamper, and the heavy steel mechanism to catch the projectile and ensure it was properly seated. It did not contain electronics or safety systems in order to avoid the need for periodic maintenance. The front end also did not have any components typically associated with starting the chain reaction in the supercritical material. A unique feature of South Africa's gun-type design was that it did not use a neutron initiator. The devices were designed to use background, or stray, neutrons to initiate the chain reaction. Calculations showed that the chain reaction would start within a few milliseconds after the HEU projectile hit the fixed HEU component. However, a downside is that the front end had to catch and hold the HEU projectile long enough for a stray neutron to start the chain reaction. Ensuring that one piece would fit into another and stay put required careful design. The front end had a relatively heavy damping component and a way to stop the projectile from bouncing back. With these design features, once a front end was built and tested, it required no maintenance and could

[8] See for example, *Armament and Disarmament*, op. cit., pp. 83-87.

remain stored in the vault. The ability to permanently store the front end was an important part of South Africa's control philosophy to ensure that a weapon could not be assembled unless authorized by the State President.

The back end contained the HEU plug, the propellant, the ignitors, the fusing and firing circuits, and self-destruct mechanisms. The back section needed maintenance by Circle personnel, requiring its periodic removal from the vault.

According to an Armscor official, a front and back end were never worked on simultaneously. Each section was kept in a separate vault inside the main vault. Moreover, a single person could not open a vault where each half was stored.

Figure 13 shows the outer doors of the vault at Circle, as they appeared after the program had ended and the area had been modified. Inside the main vault are ten separate vaults on two levels (figure 14). A back and front half would not be stored in the same vault.

Figure 13 Outer doors of the high security vault at Circle, showing the inner vaults as they appeared on a visit by one of the authors in August 2002. The outer wooden doors were added after the end of the nuclear weapons program as part of a strategy (later abandoned) to deny the existence of the nuclear weapons program (see chapter 9).

Figure 14 The inner vaults.

The inner and outer vault doors were equipped with a range of locks and control panels restricting access. Figure 15 shows the outer vault doors closed.

Figure 15 Closed outer vault door and close up

The vault had an inner control panel that controls the ten inner doors (figure 16). A keypad can be seen. A control panel was also in the plant manager's office on the second floor of Circle. He had video surveillance of the vault and had to approve access to the vault. The doors of the inner vault had two locks (figure 17).

Figure 16 Control panel inside the main vault for the inner vault doors.

Figure 17 A closed inner vault door that shows two locks

To prevent an unauthorized assembly of a whole weapon, while allowing periodic maintenance of the back half, the removal of the front end from an inner vault was tightly controlled under the authority of the State President. The front half could not be removed from the vault without specific orders from the President, via two separate military and civilian chains of command.[9] Wide representation helped ensure that no one government entity could assemble the weapons

[9] Nic von Wielligh and Lydia von Wielligh-Steyn, *The Bomb* (Pretoria: Litera Publications, 2015), pp. 172-173.

itself. For removal, the President would give an order to both the Minister of Defense and Minister of Minerals and Energy Affairs, who in turn would order the Chairperson of the AEC and the Chief of South African Defense Force to delegate their representatives, who would each possess a code. Both codes would be necessary to insert into an inner vault to retrieve a front end.

The removal of the back end was easier but still required four people with different codes, according to a senior Armscor official. All four would have to be on-site. No one person had all four necessary codes. The four people had to include a military representative, someone from the Atomic Energy Corporation, and a senior Armscor official.

The President exercised one additional positive control prior to the delivery of an assembled weapon by the South African Air Force (or its detonation at the Kalahari test site), according to a former leader of the nuclear weapons program. Air force bases were well equipped to handle the nuclear weapons. They had special logistics facilities and equipment for the storage, control, handling, maintenance, and support of nuclear weapons.[10] The warhead halves would be bolted together only on the "flight line."[11] To allow the assembling of a front and back half in the field, Circle built and stored a special portable assembly jig; however prior to the warhead's delivery, the President had to send an affirmative instruction to the air force base in possession of the weapon.

The HEU was also tightly controlled. At the beginning of each work day, the HEU scheduled for use in a manufacturing area was carefully weighed to the nearest 0.1 gram before being checked out of the vault. At the end of each day, the material was removed from the processing and manufacturing areas and weighed to a similar precision before being returned to the vault. HEU was not stored in process lines.

Circle personnel needed top secret security clearances. Only native-born South African citizens with no other citizenship could receive the necessary security clearance. Contact with people outside the program was tightly controlled and movement into and from the Circle complex was carefully orchestrated to avoid program personnel being seen.

Safety

Circle engineers carefully studied failure modes and effects and conducted theoretical nuclear criticality analysis under a range of postulated storage, delivery, and accident scenarios. According to Armscor, the devices exceeded safety requirements for this type of device, and "subsystems were subjected to strenuous tests to insure that reliability and safety criteria were met." Some of this care was dictated by the reliance of the design on a relatively large amount of HEU. The devices had enough HEU so that they were near critical if fully assembled. One former senior member of the program said that a wet hand inserted between the two parts of an assembled device could cause a criticality accident. This design limitation required extra care.

[10] *Armament and Disarmament*, op. cit., pp. 75 and 88.
[11] *Armament and Disarmament*, op. cit., p. 88.

A common safety concern with gun-type devices is that the propellant will accidentally fire, sending the projectile into the fixed end, causing a nuclear explosion. Another danger is that the projectile will accidentally slide down the barrel. At a minimum, this would ensure a criticality accident, risking workers and contaminating the adjacent area.

To prevent such accidents, each device had mechanical safing mechanisms. One blocked the projectile from reaching the other end. The first attempt did not work adequately; in the mid-1980s, one model was tested by dropping it and igniting the propellant, but the safety system did not prevent the projectile from reaching the core. It took a year and a half to fix the problem, and later versions performed well. The basic idea of the safety system was that when the device was disarmed, the barrel opening did not line up with the opening of the stationary HEU target in the front part of the device. When the device was armed for detonation, the barrel would rotate so that the openings would line up.

Another related safety system dissipated the pressure caused by the propellant firing, reducing the speed of the projectile. Holes in the barrel were left open to disperse the pressure generated by the propellant's accidental firing. The holes were closed only after the device was armed.

As a fail-safe, the devices were outfitted with a non-nuclear self-destruct mechanism. This mechanism was located in the back end.

Arming of the device would have occurred only seconds before detonation. If a positive signal to arm the device was not received from the Buccaneer aircraft, the warhead would have automatically self-destructed.

Transport containers were carefully constructed with safety in mind. Air-transport containers, such as those used to transport a device to the Kalahari test site, were designed to survive an aircraft crash and fire, according to a former senior official of the program.

1985 Government Decision to Limit Program

As Armscor was developing its ability to build deliverable warheads for the Raptor in the early 1980s, the South African government decided to put limits on the nuclear weapons program in September 1985. According to a then-senior nuclear official, President Botha recognized that the cost of the weapons program could escalate significantly. The government's rationale for limiting the program was a worsening economic crisis. However, the cost and effort to maintain South Africa's conventional military capabilities and to procure advanced weaponry in the mid-1980s, according to a declassified CIA National Intelligence Estimate, "strongly suggest that [in the mid-1980s] a nuclear weapon is far down on the military's shopping list."[12] One Armscor official said that the nuclear weapons program was "always very poor."[13]

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[12] Director of Central Intelligence, *Trends in South Africa's Nuclear Security Policies and Programs*, National Intelligence Estimate, October 5, 1984, declassified version.
[13] Interview by one of the authors, October 31, 1994.

The government decided to take ten steps:[14]

- Order the manufacture of a maximum of only seven gun-type, type A, warheads with a yield of 5-20 kilotons;
- Carry out engineering development of implosion type warheads;
- Carry out limited research and development of boosted gun-type warheads (type A*) with a yield of about 100 kilotons;
- Continue theoretical work on all other types of nuclear explosives including thermonuclear designs (B types);
- Continue efforts to integrate the payload to the long-distance carrier, a phrase for a ballistic missile.
- The production of plutonium warheads to be discontinued, but expertise developed with lab-scale production must be preserved, with the emphasis on fission element and transuranium element research. Only a limited program is envisioned;
- Limit the production of lithium 6 to a fixed quantity (about 40 kilograms), which must be stored for future use;
- Stop work on plutonium-based nuclear weapons, but maintain existing know-how.
- The Gouriqua reactor project is continued for civil purposes and to keep open option for the future production of plutonium and tritium, if necessary. However, the AEC was unable to sustain the program with its own funds. The AEC tried unsuccessfully to turn the reactor into a test facility for pressurized-water reactor fuel, but the program ended in 1989 or 1990. The Gouriqua site was never developed beyond some rudimentary civil engineering preparations;
- With a view of cost savings, limit production of HEU in the Y Plant to enough for seven weapons and a prudent reserve stock.

Producing more devices.

However, these 1985 limits did not have much impact on the day-to-day operations then on-going at Circle. With such stringent reliability, safety, and security specifications, weapon production had been slow and only two nuclear devices weapons had been made by the time the program was limited to a total of seven devices.

In 1985, the Circle engineers were mainly focused on developing pre-production gun-type models, referred to as the 300 series. They were built to test the reliability of various components, to integrate the nuclear core into a bomb casing, and to conduct tests with delivery systems. A total of six devices in this series were built. Most were used for testing. Only two in this series were eventually armed with HEU.

- Model 301 was incomplete and used for flame tests
- Model 302 was complete and used for practicing the integration of the full device and for several firing tests
- Models 303 and 304 were used for flight tests

[14] *Meeting of Ad Hoc Cabinet Committee Under the Chairmanship of the Honourable State President on Tuesday 3 September 1985 at 15H00*, *The Bomb*, op. cit., pp. 480-483.

- Model 305 was a complete device built as a spare device for flight tests. However, its quality was sufficient to allow it be provided with HEU. Later, the HEU was removed and transferred to Model 502 in 1988. Afterwards, model 305 was used for training.
- Model 306 was the final one built in the 300 series; its quality was sufficient to upgrade to an active device in 1988 and 1989.

There exists evidence of model numbers greater than 306, such as 308 and 309, but these models were not completed, according to South Africa's declarations to the IAEA. They refer to subsystems that were at different stages of development.

Model 305 was fitted with HEU in the fall of 1986, bringing the number of nuclear devices to three. Later, HEU was put in model 306. Only model 306 remained fitted with HEU at the end of the program in 1989. Model 305's HEU had been moved to a production model, and the model minus HEU was being used as a training model.

Circle started to finally produce production models, named the 500 series, in 1987 and 1988. These were originally codenamed Bakker but later called Hamerkop, or hammerhead in English. Like the 300 series models, they were all guided glide bombs for the Raptor long range weapon. They had a yield of 20 kilotons and used about 56 kilograms of weapons-grade uranium in their cores. Table 1 shows the schedule of builds into 1989, when the program was cancelled.

By 1989 Armscor had mastered the routine manufacture of gun-type nuclear weapons able to meet Armscor's rigorous safety, security, and reliability specifications.[15] Most of the weapons were manufactured after 1987. One Circle employee said that 1987-1989 was a period of considerable stress for employees at Circle.

Up until the program was cancelled in 1989, a total of eight nuclear devices with HEU were made, and two were retired. At the end, there were four 500 series devices. As mentioned above, another device was incomplete at the end of the program; the core and some non-nuclear components for this device were finished. This was to be a production model.

By 1989 according to an Armscor official, the annual operating expenditures were about 20 to 25 million rand, or approximately 125-160 million rand in April 2016.[16] The latter is equivalent to about $8.5 to 11 million at an April 1, 2016 exchange rate. In the early 1980s, the annual budget was about 10 million rand, or several million dollars a year.

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[15] Interview with Armscor officials, Circle building, February 1994.

[16] Inflation Calculator: http://fxtop.com/en/inflation-calculator.php?A=100&C1=ZAR&INDICE=ZACPI1958&DD1=01&MM1=06&YYYY1=1989&DD2=01&MM2=04&YYYY2=2016&btnOK=Compute+actual+value

Table 1 Production Schedule of South African Nuclear Explosive Devices(1)

Name of Device	Rear or Front Part	Production Date of Part or Device	Comments
Video/Melba	?(2)	November 1979	Manufactured at Pelindaba, moved to Circle in 1982 and HEU core was replated; afterwards renamed Melba. A test device.
Hobo/Cabot	n.a.(2).	December 1982	Shaped HEU components made at Pelindaba, but rest of device made at Circle; Unknown when device renamed.
305	Rear Front	September 1986 November 1986	Upgraded pre-production model; HEU removed and reused in 502(3)
306	Rear Front	June 1988 June 1989	Upgraded, pre-production model
501	Rear Front	August 1987 June 1988	Production model
502	Rear Front	November 1988 October 1988	Production model; HEU from 305
503	Rear Front	November 1988 March 1989	Production model
504	Rear Front	March 1989 March 1989	Production model; HEU from Cabot
Set 7		Not completed	Production model

Notes and Comments

(1) Unless otherwise noted, devices were made at Circle and were deliverable by aircraft.
(2) Information not available on whether it had a front and back end.
(3) Model 305 continued to exist as a training model without HEU.
(4) A total of eight active devices were built. One device was dismantled and the other placed on an inactive status as a training model. Thus, at end of program, there were six active devices, one active device under construction, and at least one device that was, at least, originally qualified to be armed with HEU.

Making the Devices

Armscor developed a sophisticated manufacturing system to make gun-type nuclear weapons. Despite its sophistication, most of the manufacturing steps were straightforward. As can be seen in figure 9, the manufacturing operations were under the engineering, technology development, and operations sections, which reported directly to the plant manager.

A former senior nuclear weapons official stated in 1994 that South Africa realized that it could develop a nuclear arsenal without significantly running afoul of international export control efforts, which were considerably weaker than today. In the 1980s, much of the equipment could be bought on the open market without much scrutiny. Once bought, it was sometimes copied as necessary.

The process of making a nuclear weapon started with the receipt of HEU metal billets from the AEC (formerly the AEB). After measuring its mass and enrichment level, the HEU was placed in the high security vault.

The first manufacturing step was to cast the HEU metal into the rough shape of a nuclear weapons component. The South African design did not cast HEU hemispheres but several sections that were later joined together to make the final HEU pieces, or apparently rings, for the gun-type design. A mold was prepared and on the day of the casting, the necessary amount of HEU was carefully checked out of the vault. The operators melted the HEU in a German-made Degussa vacuum furnace and poured it into the mold. Circle depended on two vacuum furnaces. The first was bought abroad in the 1970s. The second was made by South Africa. The latter was a backup that could be used if the first furnace broke. The backup furnace had not been used by the end of the program.

The casting operations occurred in the metallurgy room. Figures 18 and 19 show different views of this area as it appeared in 2002 after the room had been emptied, the walls and original floor removed, and the area thoroughly decontaminated following the end of the program in 1989. After inspection and material accounting, the molded metal was placed back in the vault. The casting area was also decontaminated.

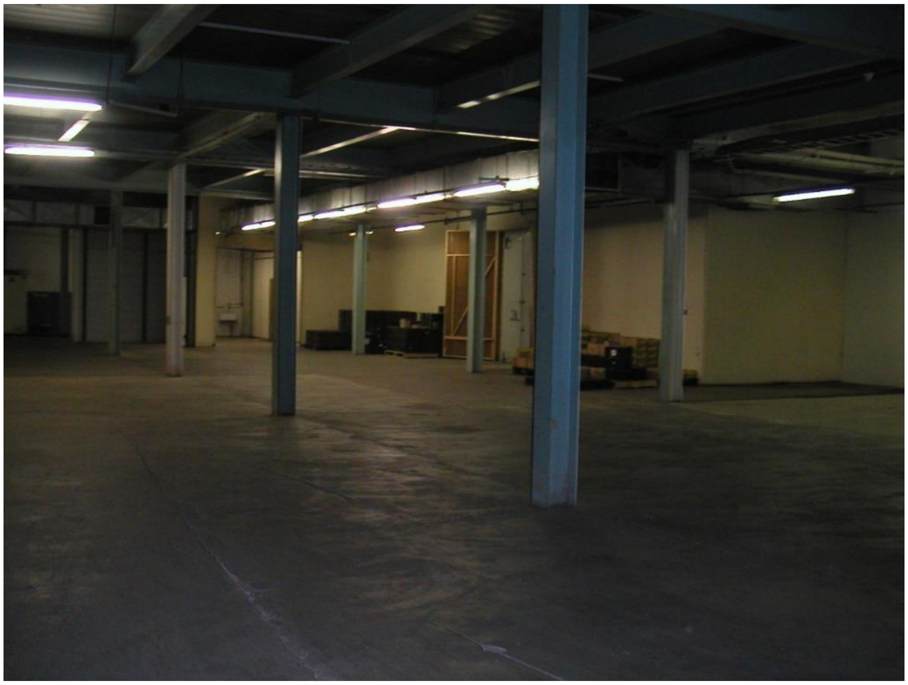

Figure 18 A view of the metallurgy or “uranium” area in Circle, after the removal of the walls and equipment. The outer vault doors are visible in the background.

Figure 19 A view of the metallurgy or “uranium” area in Circle, after the removal of the equipment and walls. The barrels and boxes are unrelated to the nuclear weapons program.

The next step in the process was to machine a casted piece or section of the HEU core. Lathes outfitted with special fittings machined each uranium casting. One lathe was used to machine the HEU components and another one machined the depleted uranium components. The latter were not used in actual weapons but in models. Easing their manufacture, the components were in segments that were alloyed together later into the final HEU core component. The lathes were in inert cabinets with hoods. The room that contained this equipment can be seen in figure 20. These lathes were not sophisticated, lacking numerical control. The weapon program depended on using a clever design for the HEU components and good machinists to compensate for the simplicity of the lathes. The machining areas were well filtered and any liquid material was collected in a pit and pumped into a cart. Material containing HEU, including in liquid solvents, cut-offs, and shavings, was carefully collected. The finished piece was placed in the vault and the area was decontaminated.

The machining area was in a closed room adjacent to the metallurgy room (see figure 20). It contained two lathes, hoods, and ventilation equipment.

Figure 20 Two views of the machining area of the Circle plant in 2002. On right photo, boxes are unrelated to nuclear weapons program. Photo on the right is from inside the machining room looking into the metallurgy area.

After retrieval from the vault, each HEU section was plated with nickel to protect it against oxidation or corrosion. Afterwards, each section was returned to the vault.

The casting and machining operations generated scrap and nuclear waste, which were sent to the Atomic Energy Corporation for recovery or disposal. The shipments were sent at night to minimize detection.

There were many non-nuclear parts that had to be procured from outside suppliers or made on-site. A Master Record Index (MRI) contained all the necessary drawings and specifications. Many non-sensitive parts were procured from outside the organization. These electronic and standard parts and components were purchased externally through an open tender system.

Sensitive parts were manufactured at Circle. It made certain electronic parts, including firing circuits, PC boards, and certain electrical devices that initiate a mechanical action (“electro-mechanical devices”); the barrels; the tampers; the metal damper or stopper pieces; and stainless steel sleeves or shields surrounding the tamper. In addition, it made the ignitors for the propellant and the propellants. Some of these items were made in a workshop (see figure 21) that was right off the center bay of the building. Equipment included two and three dimensional milling machine tools, inspection equipment, ball mills, lathes, and furnaces. At the end of the program, a five-axis Takisawa MAC-V2 milling machine had been procured for Circle, although its purpose is unknown. There was also a gauging shop in Circle that could provide accurate instrumentation for measuring weapon components and produce shapes or reference components used to check manufactured items. When entering the building, a large store room was directly left of the central bay of Circle (western side) for raw materials and spare parts (see figure 3).

Figure 21 The former workshop in 2002 after it was emptied of equipment following the end of the nuclear weapons program.

The tamper of the device, made from tungsten, was sensitive and difficult to make. It was composed of orange peel shapes glued together into a shell. The raw material was tungsten powder, which was ground in a ball mill, placed in a rubber bag, and pressed in a cold isotopic press (CIP). The CIP was made in South Africa. After inspection, the solidified powder was heated, or sintered, in a special oven that had been purchased from Degussa-Durferrit. Afterwards, the pieces were machined and glued together. Tamper (and steel shield) elements were made for the HEU plug as well. Figure 22 shows the oven and control panel.

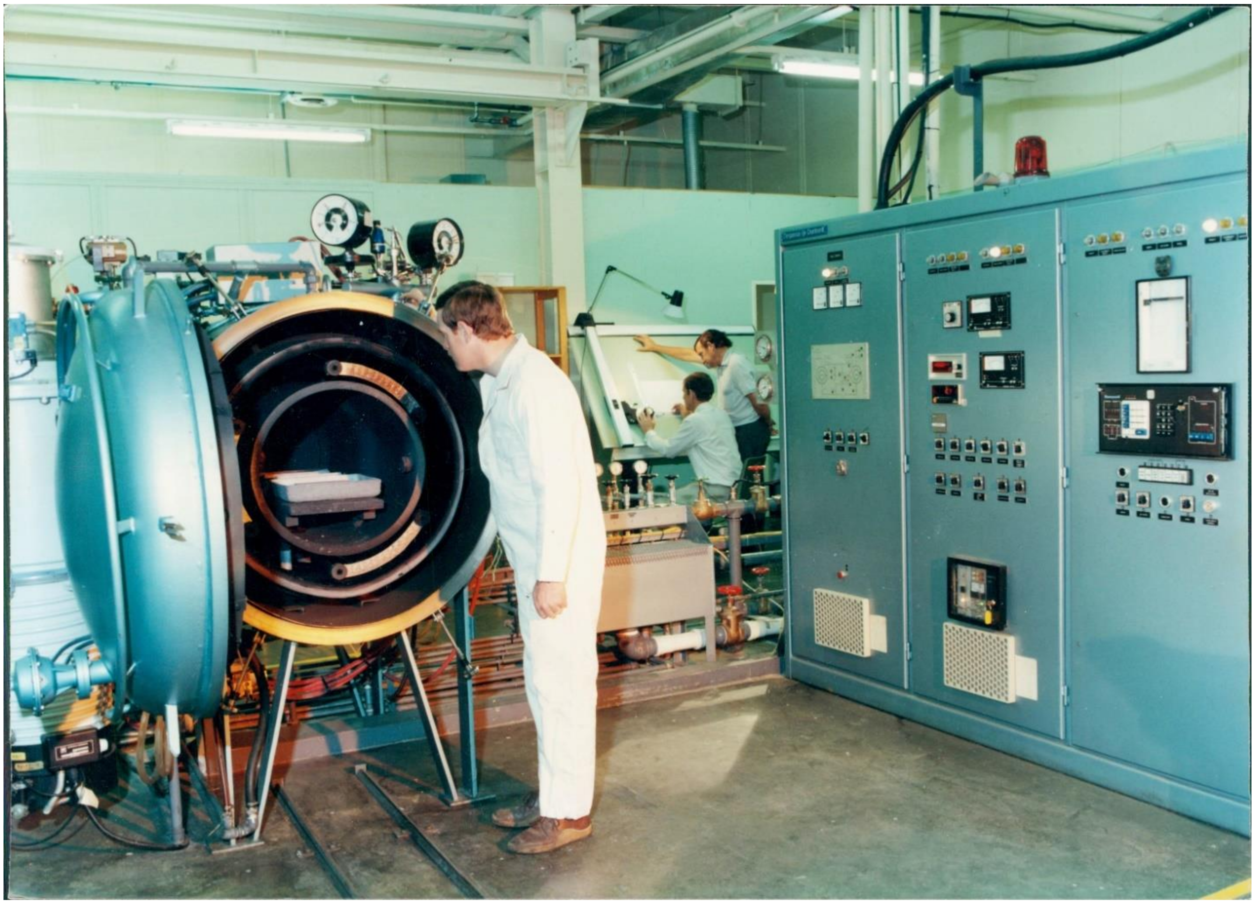

Figure 22 Vacuum induction furnace in Circle workshop that had earlier been used to sinter the tamper subcomponents. The furnace was manufactured by Degussa-Durferrit and has Honeywell control equipment. Photo source: Armscor

The parts and subcomponents had to be integrated, or assembled into a front or rear section of the nuclear device. To ensure adequate security, a front and rear end were never integrated simultaneously. Figure 23 is a simplified schematic of the integration process.

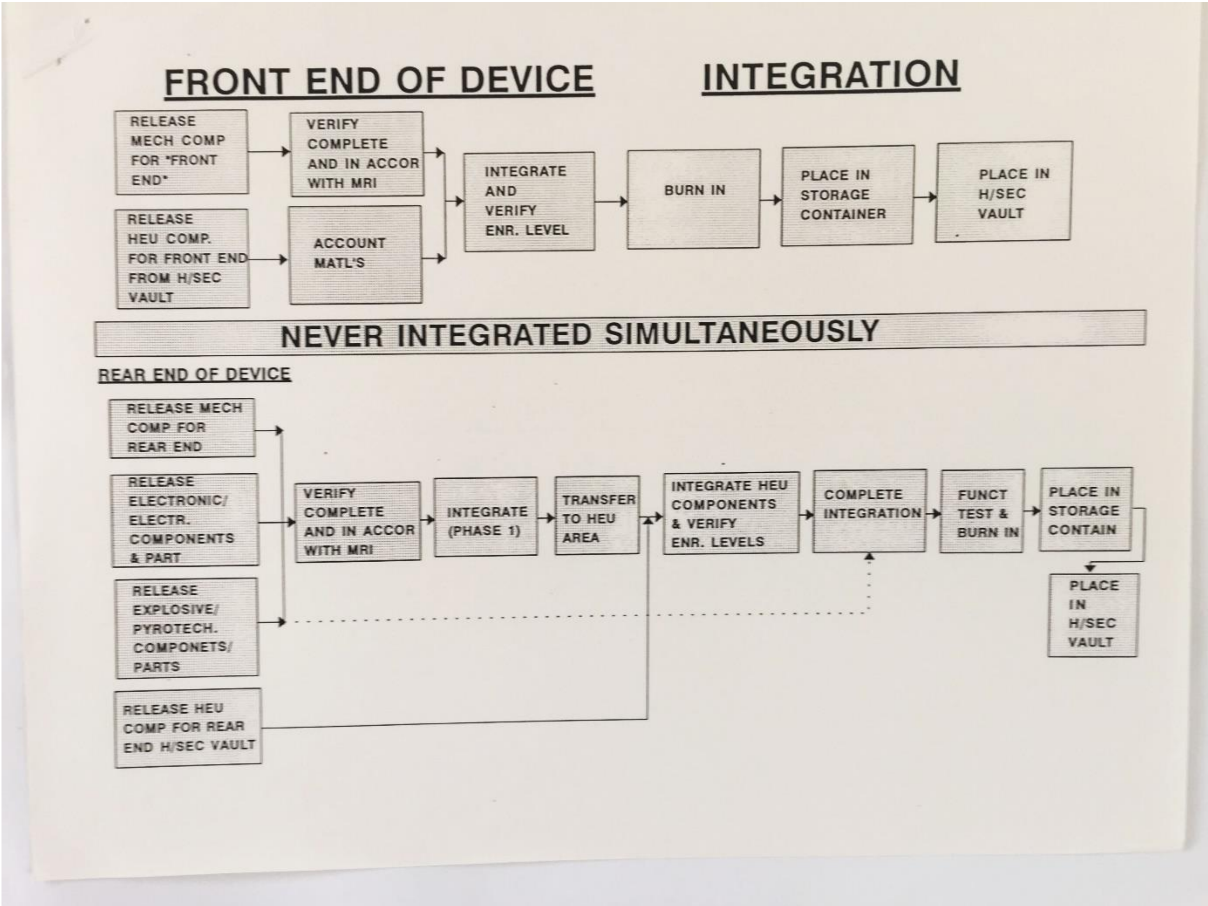

Figure 23 Schematic of steps in assembling a front or rear end of a nuclear device, where enr. is enrichment, H/Sec is high security, MRI is Master Record Index, and accor is accordance.Source: Armscor

A special part of the integration process was called the "burn-in" which was done at the nearby environment test facility. Testing at this facility was necessary to ensure that the nuclear weapons could withstand being transported and launched.

Figure 24 and 25 show opposite ends of the environmental test facility, which was built into the hillside. It had doors on each end to allow vehicles to drive through the building. Figure 26 shows the facility from the bridge over the oval high speed test track. The facility was made out of concrete since it was designed to handle high explosives (up to 30 kilograms).

Figure 24 Environmental test building from side opposite the Circle building.

Figure 25 Environmental test building, the end closest to the Circle building.

Figure 26 Environmental test building in the distance as viewed from the bridge over the oval test track. The Circle building (not visible) is to its left.

After manufacturing in the Circle facility, a front or back end would be sent to the environmental testing facility for burn in (figure 27). It would be shaken, and put in a humidity cabinet and an environmental oven. The testing evaluated the effect on the weapon as it was cycled through temperatures and changes in air pressure.

Inside the test facility, one set of tests ensured that the warhead would survive the considerable vibrations encountered on take-off, particularly when it is mounted under an aircraft wing. For such tests, the facility had both a large and small vibration table. They were capable of generating random and large periodic vibrations. The vibration table needed cooling so cooling towers were built behind the building. Armscor had difficulty buying the vibrators, especially the large one, according to a former senior Armscor official, since they are only used by the military. According to a former senior member of the program, "Their purchase was quite a headache."

The building was also equipped with a 200g centrifuge. It also had two climate testing chambers, at least one of which could simulate humidity and altitude up to 50,000 feet, at 99 percent relative humidity, and achieve temperatures from -60 to +130 degrees centigrade.

After the testing was complete, the half would be returned to the vault at the Circle building. In the case of the front ends, once burn in had occurred, they would not come out again for maintenance.

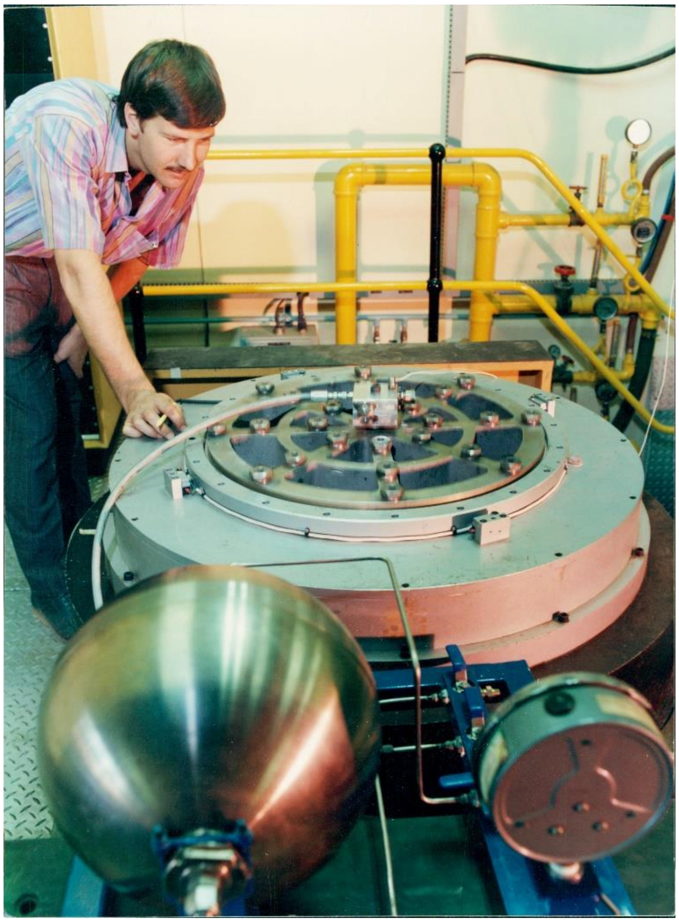

Figure 27 Testing equipment at the environmental test facility. Source: Armscor

Taking Stock

Overall, Armscor was creating a small but formidable nuclear weapons arsenal at Circle. The weapons program had benefited from Armscor's independent development of a highly accurate standoff weapon to build a credible nuclear weapon system. Its emphasis on reliability and safety ensured that the South African defense forces would have confidence in this weapon system, if it ever had to be deployed. South Africa's development of a ballistic missile in the late 1980s would motivate the next phase of its nuclear weapons production ambitions.

However, key personnel in the nuclear weapons program believed that the nuclear strategy needed further refinement. André Buys, who had risen in stature in the weapons complex, obtained a mandate in the early 1980s to lead a team in creating a more sophisticated strategy that would help guide the next stage of South Africa's nuclear weapons.