Chapter 2 Developing Nuclear Devices

To a small number of key scientists and engineers at the Atomic Energy Board (AEB), the 1970s started with work on what they believed was a peaceful nuclear explosive (PNE). The goal was to complete the first "type A," or gun-type device, when the Y Plant had finished making enough highly enriched uranium (HEU), planned originally for mid-1977. Once both efforts converged, the plan called for an underground test of the device. However, the actual date when the first device could be assembled would turn out to be two years later. Although the device development and test site construction were completed as planned, the production of enough HEU was delayed two years.

When the PNE program formally started in 1971, André Buys was a young engineer beginning his career at the AEB. He had received funding for his university training from the AEB with the proviso that he would work for the AEB afterwards. In 1971 he was assigned to the PNE project at Pelindaba that was just taking shape, but as he worked in the program, Buys was increasingly troubled. He saw no reports that PNEs were viable economically or technically. He often asked his superiors what would be their purpose. His superiors told him that they would find a use for them and encouraged him to focus on this interesting scientific and engineering work. Whenever he asked if it was really a bomb program, he was told no. Buys developed an impression that the AEB under Ampie Roux could easily obtain funds from the government to do what it judged important, and the AEB viewed the prospect of developing PNEs as an exciting technical challenge, one that could occupy the defunct Pelinduna reactor team. Yet developing an agreement of the purpose and scope of what would gradually become a full-blown nuclear weapons program would drive Buys throughout his career, first at the AEB and then as a leader of the nuclear weapons program in the 1980s at the Armaments Corporation, or Armscor.

Reactor Development Division

With the cancellation of the Pelinduna reactor project and the start of the PNE program, the Reactor Development Division was transformed into an organization centered on the major tasks of building a nuclear explosive device, absent delivery system integration. Its primary task was developing a gun-type nuclear device, but in parallel, it started rudimentary work on implosion-type and thermonuclear devices.

The old names of the Division were preserved, serving as crude codenames for the new PNE work. In their authoritative book *Armament and Disarmament: South the Africa's Nuclear Weapons Experience*, Hannes Steyn, Richardt van der Walt, and Jan van Loggerenberg, all of whom participated importantly in the former nuclear weapons program, describe the new responsibilities of the key groups for making PNEs in the transformed Reactor Development Division:[1]

- Nuclear Engineering Group studied the possible civil applications of nuclear devices in South Africa. It established a rock mechanics laboratory to determine the effects of an underground explosion on the surrounding geology and to develop methods for plugging

[1] Hannes Steyn, Richardt van der Walt, and Jan van Loggerenberg, *Armament and Disarmament: South Africa's Nuclear Weapons Experience* (Pretoria: Network Publishers, 2003), pp. 38-39.

the test shaft so as to prevent the release of radioactive elements. It also conducted experiments with conventional explosives to calibrate computer programs being developed to predict the effects of underground nuclear explosions.

- Theoretical Reactor Physics Group developed computer codes for the design of nuclear devices, including neutron data, criticality studies, and explosive yield estimates. Their work was based on earlier work on thermal reactor designs.
- Theoretical Nuclear Physics Group estimated pre-detonation probabilities and material properties at the extremely high temperatures and pressures of a nuclear explosion. This group also was responsible for theoretical designs of possible future thermonuclear devices.
- Experimental Reactor Physics Group, which was originally responsible for the Pelinduna critical facility, built a critical facility and a fast pulse reactor. It also developed the equipment for measuring the reactor's dynamic properties, as well as planned for the collection of data at a possible fully instrumented nuclear explosion.
- Reactor Engineering Group was in charge of obtaining sensitive high pressure and temperature data unavailable in the open literature. It developed and operated the necessary equipment to acquire these data. It was also responsible for the engineering design of nuclear devices, as well as the manufacture and assembly of nuclear explosive devices.
- Electronic Engineering Group identified and then built or procured all the electronic equipment for the entire program.
- Process Metallurgy Group was responsible for uranium metallurgy, particularly in developing the methods to convert HEU hexafluoride into metal, which is the chemical form most desirable for nuclear explosions.
- Physical Metallurgy Group developed and deployed methods to melt, cast, and machine enriched uranium into suitable geometries with tight specifications. It was also charged with producing all other metallic materials for the program.
- Nuclear Chemistry Group handled investigations into the production of thermonuclear materials.

With an enrichment program expected to make a considerable amount of weapons-grade uranium (WGU), the PNE program decided to first focus on making a gun-type nuclear weapon. This type of weapon requires a great deal of WGU but is generally viewed as easier to build than an implosion-type, which would require less than half the amount of WGU.

However, the Reactor Development Division did not have the experience to work with propellants or understand ballistics sufficiently for the firing of a WGU plug down a barrel to mate with the rest of the WGU, achieving a supercritical reaction.[2] There was also concern about the noise involved in repeatedly firing a gun-type device, albeit one with a surrogate material, at the Pelindaba site. By the early 1970s, this site housed a considerable number of personnel and visitors who did not know about the PNE program. As a result, the decision was made to build a temporary test and development facility at the National Institute for Defense Research (NIDR) of the Council for Scientific and Industrial Research at Somerset West (later part of Somchem) (see figure 1). Located in the Cape Province, this military facility was already

[2] *Armament and Disarmament: South Africa's Nuclear Weapons Experience*, op. cit., p. 39.

involved in the development and manufacture of explosives and propellants, so a small research facility studying a gun-type device would not stick out as it would at Pelindaba. Moreover, this institute had the experience in making guns and propellants and sophisticated measuring equipment. Buys observed that the relatively small facility dedicated to developing a gun-type nuclear explosive was the least noticeable of the facilities at Somerset West.[3]

A small team of three engineers from the Reactor Development Division, including Buys, were sent in 1972 to this site to carry out research and development work on the mechanical and pyrotechnical subsystems of a gun-type device. They started with a shortened naval gun to fire the projectiles.[4] The NIDR staff aided the AEB personnel in developing expertise in both propellants and ballistics.

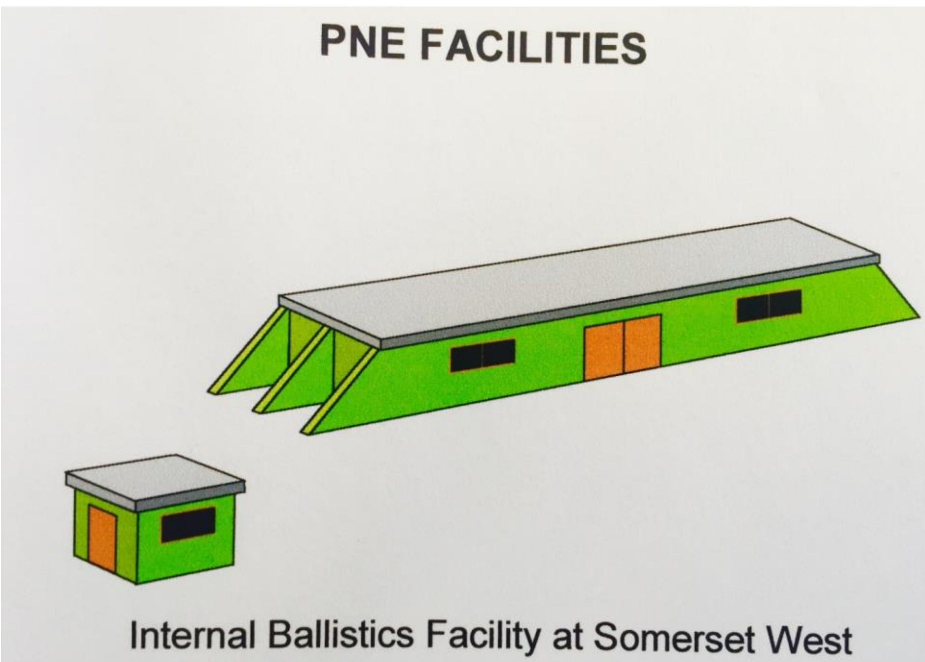

Figure 1: A schematic of the facility at Somerset West involved in developing the gun-type nuclear device in the early 1970s. Credit: André Buys

At the new site, South Africans worked on the mechanical and pyrotechnic subsystems for a gun-type device. The first experiment at the internal ballistics test facility was conducted in September 1973. The team fired heavy (50 kilogram) tungsten projectiles from a bored-out four inch naval gun. Internal ballistics parameters were measured for a theoretical model for the

[3] Interview with André Buys, January 23, 2003.
[4] *Armament and Disarmament: South Africa's Nuclear Weapons Experience*, op. cit., p. 39.

device, according to the South African declaration to the International Atomic Energy Agency (IAEA).

Using this information, the team designed a scale model which, with a projectile constructed of tungsten, was tested at Somerset West in May 1974. This demonstrated that a nuclear explosive was feasible. The team tested, with extensive instrumentation, the first full-scale model of the gun-type device using a natural uranium projectile in 1976. This test proved the mechanical integrity of the design.

In designing the device, the AEB team at Somerset West faced several challenges, including achieving the repeatability of projective velocity and symmetry requirements when the projectile flies into the core.[5] The latter meant that the end of the device had to be reinforced -- in essence it caught the plug fired down the tube. This unique approach was necessitated by the lack of a neutron initiator, a device that generates neutrons to start the chain reaction in the supercritical material. South African 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 merged into the fixed HEU core. Thus, for a nuclear explosion to occur, the shape of the assembled highly enriched uranium had to be spherical for at least on order of milliseconds, one of the more challenging engineering feats the team had to overcome.

Because nuclear weapons information is generally classified, the South African program lacked key information about gun-type nuclear devices and other designs. Through research and development efforts, it learned certain classified information. However, according to one of the participants, people in the South African program had the idea to monitor open source publications by top US nuclear weapons experts. After assembling a list of their names, South Africans searched their publications and realized that these experts were publishing highly useful nuclear weapons information piecemeal or couched within civil subjects.

In 1974 unable to answer certain pressing questions about the gun-type device, an engineer working on it at Somerset West went to the United States to attend a high explosive conference where leading US nuclear weapons experts were to deliver talks. Posing as an employee working on civil high explosives at the Council for Scientific and Industrial Research, South Africa's leading civilian scientific and technology research organizations, he had ample opportunities to ask detailed questions of the US nuclear weapons experts. He was pleased that these experts engaged in discussions with him in which they were frank and helpful.

However, South Africa later saw this type of approach as a security risk and discontinued it. The South Africans realized that the information could go the other way too. Asking certain questions could lead the US nuclear weapons experts to gain insights into what South Africa was actually working on.

For the personnel in the program, according to one leading member of the nuclear weapons program at the time, the view of the AEB was that the program could be kept secret only if the

[5] Fax from Armscor to Mark Hibbs, *Nuclear Fuel*, April 27, 1993.

first rule was: No contact with outsiders at all. Of course, in practice, this was not always possible.

PNE Facilities and Activities at Pelindaba

While the team progressed at Somerset West, other groups in the Reactor Development Division were working on other parts of the PNE program. One key question was where to house the growing number of people associated with the program while also keeping their work secret. The PNE program was growing to about 50-100 people, while the Pelindaba and Valindaba enrichment sites at the time had about 3,000 personnel. To keep the PNE program hidden from the other personnel at Pelindaba and Valindaba, and to prevent foreign visitors who could be working for intelligence services from discovering the work, the AEB decided to remove the PNE program from the main site; however, they did not want to go too far away. So, the idea was to "be close but not too close," according to Buys. In this way the program could easily still draw upon the infrastructure of the main site, including for any emergencies.

In a valley on the southwestern side of the Pelindaba site was already a staff recreation center by the Crocodile River (see figure 2). Thus, personnel were known to travel into the valley.

Figure 2 Pelindaba staff recreation area, with baboons, in early 1994.

The decision was made to put the PNE facilities on the other side of this valley. Frank Pabian, a leading expert on South Africa's nuclear programs, while a senior official at the Joint Research

Center in Italy, pointed out that this valley was hidden by a ridge, consistent with concealment via "terrain masking.[6]

By the mid-1970s, a new series of non-descript buildings were being created for all major aspects of the planned PNE program. Figure 3 shows commercial satellite images of the major facilities involved in the PNE program in the valley below the main Pelindaba nuclear site, including:

- Building 5000, also known as (aka) Hall A
- Building 5100, aka Hall B
- Building 5200, aka Hall D
- Building 5300, aka Hall C
- F1 High Explosive Magazine
- F2 High Explosive Outdoor Test Site

F1 and F2, which were further away from the main site, were a high explosive magazine and an outdoor high explosive test site, respectively. Both were used in the development of implosion-type nuclear devices. Figure 4 shows Buildings 5100, 5200, and 5300 in the valley below the main Pelindaba site. Figure 5 shows F2 in a commercial satellite image.

[6] Frank V. Pabian, "The South African Denuclearization Exemplar," *Nonproliferation Review*, 2015, vol. 22, no 1, pp. 27-52. http://www.tandfonline.com/doi/full/10.1080/10736700.2015.1071969

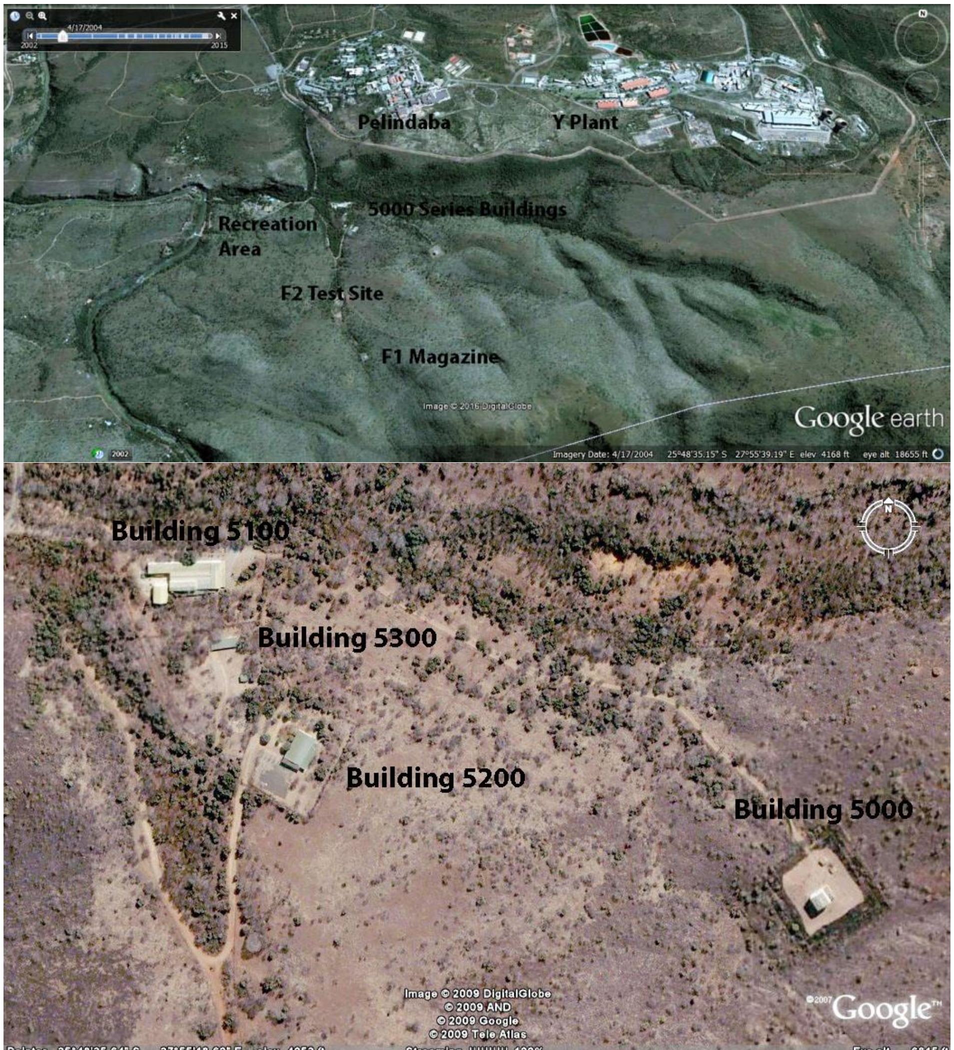

Figure 3 Commercial satellite images of the main facilities in the PNE program.

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Figure 4 Buildings 5100 and 5200 in the valley below the Pelindaba site.

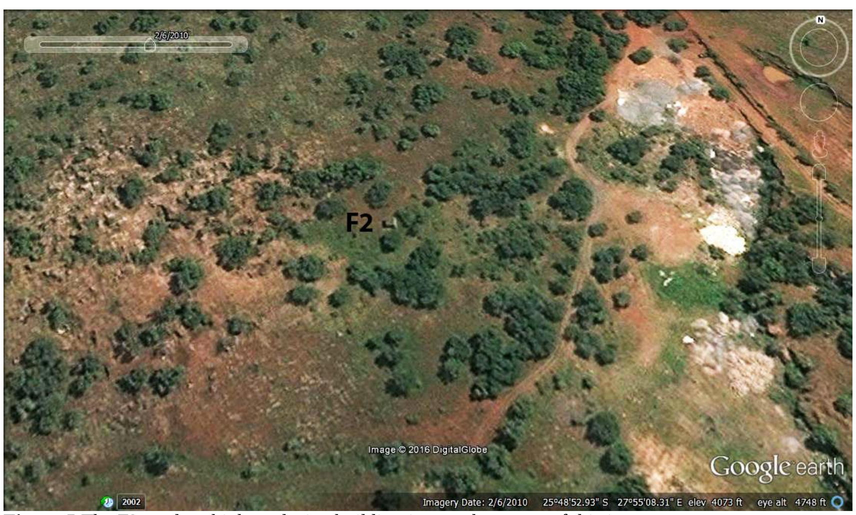

Figure 5 The F2 outdoor high explosive building is near the center of this image.

In parallel to the work at Somerset West, one of the first challenges was the development of a range of neutronic, thermodynamic, and hydrodynamic computer codes related to nuclear explosive devices. According to a former member of the team, the PNE program drew upon a team of theoretical specialists at the main site. Several members of the theoretical team had US trained in the United States and were nuclear physicists. However, some of the members were less than enthusiastic about working on nuclear explosives, according to a former member. They saw the work as a distraction of the civil nuclear work they wanted to do at the main site.

The theoretical nuclear explosive work was based in the main PNE building, code named Building 5100 or Hall B (see figure 6).

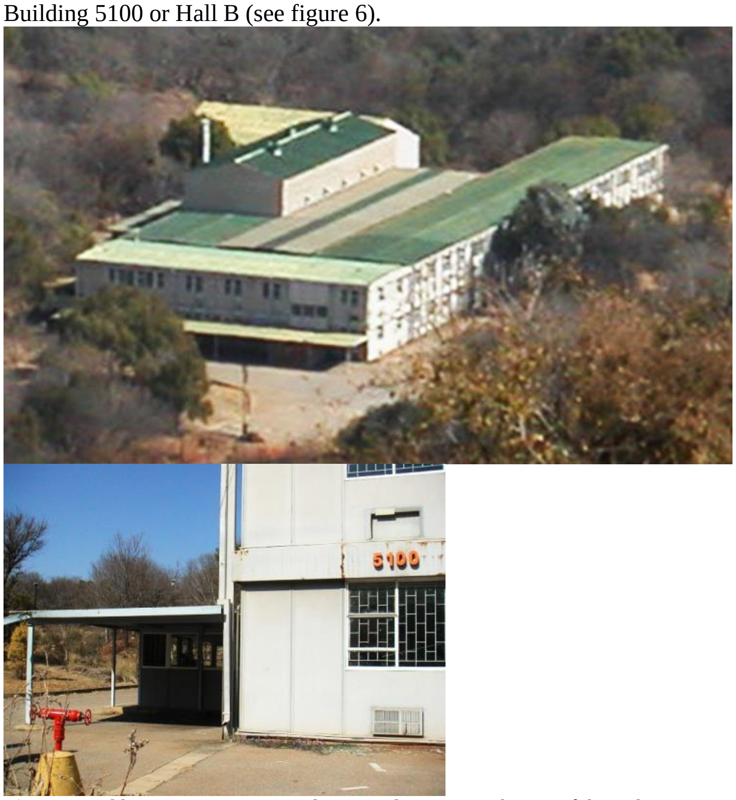

Figure 6 Building 5100, as it appeared in 2002 during a visit by one of the authors.

Figure 7 shows a vault for classified documents in the second floor hallway in the design section of the building. Members of theoretical group in Building 5100 did basic research on compression, hydrodynamics, photon cross sections and neutron multiplication, according to a former member of the nuclear weapons program.


Figure 7 Vault in design section of Building 5100.

The program needed advanced computers for their calculations. To that end, it secretly ordered one from Europe. Later, the pattern was for a civil company to order computers abroad and the nuclear weapons experts would use them off-hours or remotely, according to a former member of the nuclear weapons program.

Building 5100 also housed a small-scale light gas gun (referred to as a “six millimeter system,” by Armscor personnel) used to determine the equation of state of materials subject to high temperature and pressure, critical to the design of nuclear explosives. These essential data for uranium and plutonium are classified but are critical to the theoretical models related to nuclear explosives.

Based on the prototype gas gun in Building 5100, the program built a full-scale, two-stage light gas gun in Building 5200 that was 20 meters long (a “29 millimeter system”). Figure 8 shows the front of Building 5200 as it appeared in 2002, and its side entrance where heavy pieces could be brought into the building.

Figure 8 Building 5200, from front of the building and from side closest to Building 5100, showing entrance for heavy items, as it looked in 2002. The first nuclear explosive device was assembled in this building.

The program also needed to learn to make sensitive HEU components for nuclear weapons, too sensitive to make at the main site. These parts were made in Building 5100 in a first floor workshop located off the covered courtyard of the building and below the device design section on the second floor (see figure 9). The door was in a covered courtyard to allow vehicles to enter and unload outside the purview of overhead surveillance.

Figure 9 The door led to the workshop that made HEU parts. The door was in a covered bay in Building 5100. In photo on right, the door is hidden by the small white building.

Once HEU was available, starting in 1978 and 1979, criticality experiments were done in Building 5200, which also had vaults to store HEU. These straightforward experiments verified the neutron multiplication factors of the two parts of the gun-type device separately, providing additional confidence that the gun-type design would work. The subcritical experiments used a neutron injector designed by physicists brought into the PNE program from the main site.

One advantage of a gun-type design is that the need for a full-scale test can be replaced by a certain type of criticality test that will experimentally verify theoretical models. This type of experiment is sometimes referred to as "tickling the dragon's tail," suggesting the danger inherent in the test. In essence, a simplified "dragon" machine, or pulsed fission reactor, involves a slug of highly enriched uranium sliding down a wire or track through a cylindrical annulus of highly enriched uranium, simulating in slow motion what occurs in firing a gun-type design. The United States conducted such experiments in early 1945 at Los Alamos during the Manhattan Project.

South Africa's dragon experiment involved a pulse reactor in Building 5000, designed to verify its new nuclear device computer models. Figure X shows the inside and outside of the building as of 1994, during a visit by one of the authors. Although ready by about 1975, it was not used until 1979 when enough HEU became available. This type of reactor goes critical after inserting a final rod of HEU into a larger HEU mass surrounded by a steel reflector. The pulse reactor was designed to use a tungsten reflector, but that reflector was not finished by the time of the test. The critical reaction is stopped by the heating of the core and springs that push apart the HEU pieces. Instruments measure the neutrons produced. The 1979 experiment, according to a former senior official close to the IAEA, involved about 35 kilograms of 80 percent enriched uranium, implying a thick neutron reflector surrounded the HEU core.

Figure 10 Building 5000, where South Africa performed a dragon experiment. An overhead crane is visible in the lower image. The images were taken in 1994, when no trace of the experiment remained.

These types of experiments can be risky. If a slug had become stuck in the US dragon machine, the highly enriched uranium would have become supercritical, causing a small nuclear explosion (on order of tens or hundreds of kilograms of TNT). Thus, any dragon-type reactor must be built with safety as a primary concern, and it must be operated carefully. South Africa apparently attempted to mitigate this danger in several ways. It built Building 5000 at the bottom of a depression surrounded by hills in an isolated portion of its main nuclear site (see figure 11). The control room was in Building 5100, which was almost three quarters of a kilometer away and shielded from the reactor by a hill. After the dragon test, the reactor was never used again. The facility was shut down in the early 1980s.

Johan Slabber, the former director of the Reactor Development Division, has spoken of a "mishap" in an experiment with the pulse reactor.[7] In this case, the reactor was shut down just in time to prevent a serious radiological accident from happening.

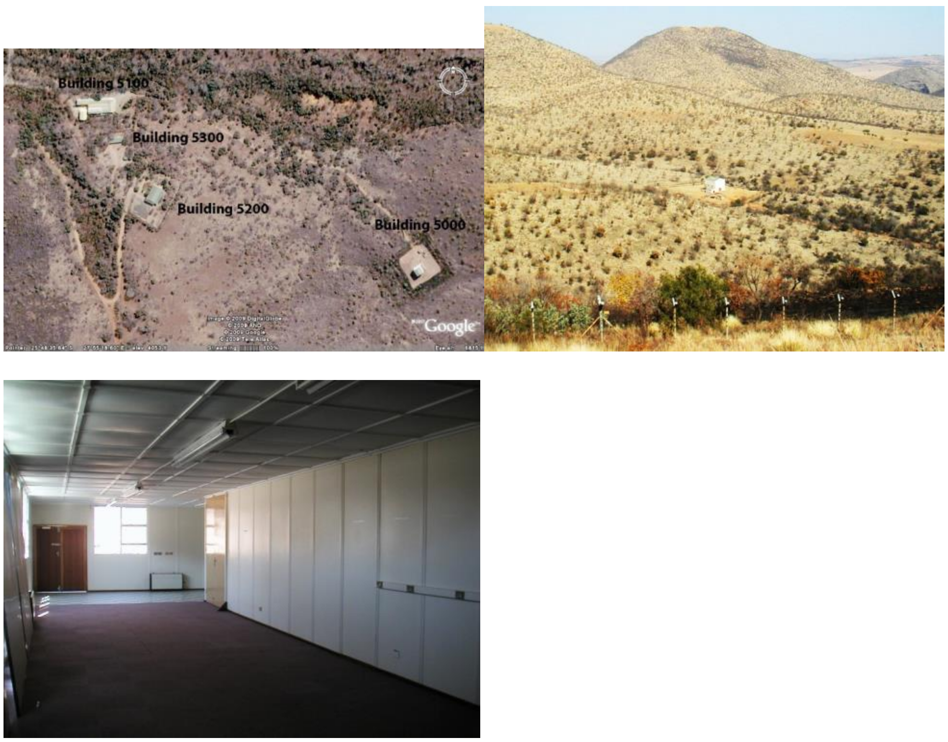

Figure 11 Building 5000 was isolated from the other facilities in a depression. The lower image is where the control room for the reactor had been located on the first floor of Building 5000, facing the reactor. All the reactor equipment was emptied from the room, years before this picture was taken in 2002.

[7] Frank V. Pabian, "The South African Denuclearization Exemplar," op. cit.

BOX: 5000 Series Buildings in the 1970s

Building 5000 - This facility contained a pulse reactor for the experimental verification of theoretical computer models. In 1979 the reactor was used as a fast critical assembly in an experiment often referred to as "tickling the tail of the dragon" that proved the design of the gun-type device. The reactor was never again used as a pulse reactor and the facility was shut down in the early 1980s.

Building 5100 - This building contained the control room for Building 5000, offices, research and development laboratories, and machining facilities for uranium metal. At its height, about 100 people worked in the building, according to a former employee from the era.

Building 5200 - This building housed a large, two-stage light gas gun. Criticality experiments using HEU were done in this building to verify the multiplication factors of the two parts of a nuclear explosive device, providing confidence that the gun-type design would work. The first nuclear explosive device was also assembled in this building in 1979. Vehicles and cabling for the Kalahari test site were kept here, in essence because this building was the staging area in case of the decision to test.

Building 5300 - This building was designed exclusively as a laboratory for high explosives. In the early stage of the South African nuclear weapons program, small quantities of high explosives were pressed and machined into shapes at this facility.

Implosion-Type Nuclear Device

The development of implosion technology was part of the PNE program from its inception. Theoretical work started in the early 1970s. However, there was no significant pressure to finish a design, given the emphasis on the gun-type device.

For example, an implosion type device would have required a neutron initiator to start the chain reaction at a critical moment. Some work was done in the 1970s on an electronic accelerator type of initiator but the work did not progress very far.

Nonetheless, the AEB did build facilities to pursue high explosive technologies associated with implosion. Building 5300 was designed mainly as a laboratory for high explosives work related to implosion technology. As such, at this facility small quantities (about 50 grams) of high explosives were pressed and machined into shapes aimed at learning about the process of imploding a spherical core. It also produced high explosives for experiments to measure the impact of an explosion on rock as part of designing the nuclear test site. Figure 12 shows the front of the building. This narrow building contained a number of concrete bays for work with high explosives.


Figure 12 Building 5300, which had a number of small high explosive cells.

Small high explosive tests for an implosion design were done at an outdoor high explosive test facility called F2. Figure 13 shows the building that held the instrumentation, while the explosive tests were detonated in front of the building. When it was used, this concrete wall and roof were covered in dirt. Nearby, a magazine, F1, stored high explosives for the program (see figure 14).

Figure 13 F2 outdoor high explosive test site, south of the 5000 buildings.

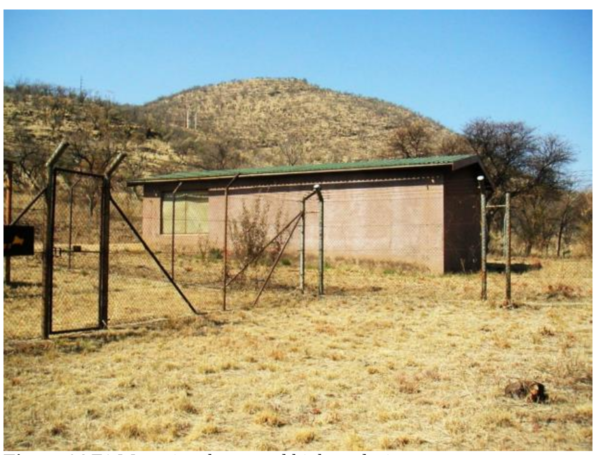

Figure 14 F1 Magazine that stored high explosives

Thermonuclear and Boosted Devices

The 1971 decision to proceed with type A devices included approval to work on a "boosted" nuclear explosive, referred to as type A*. This device was envisioned to use a mixture of lithium, tritium, and deuterium inside the fission device that would dramatically increase the overall explosive energy of the device. In August 1973, the Minister of Mining approved theoretical work on type B, or a thermonuclear device with a fission detonator, referred to as a two stage thermonuclear nuclear device.

Most of the focus of this early effort was on obtaining thermonuclear materials. In the early 1970s, the program started work on separating the isotope lithium 6 from natural lithium. Lithium 6 becomes tritium after neutron irradiation and is often used in thermonuclear devices or as a target in a reactor to make tritium. The AEB started testing a process to separate lithium 6 based on a mercury exchange progress. This work was done in Building 5100. Figure 15 shows a two-story bay, located off the covered courtyard where this work on lithium separation took place in the 1970s. A small amount of lithium 6 was produced in 1973.[8] Later in 1983, work started on an atomic vapor laser isotope separation (AVLIS) process to make lithium 6 that utilized copper vapor lasers.

Figure 15 The two-story bay where lithium 6 separation was done in the 1970s. Image was taken in 2002.

[8] Atomic Energy Corporation, "Tritium Programme," undated (about 1993), unpublished.

Building 5100 was also involved in separating small amounts of heavy water. Heavy water contains deuterium, which is also a thermonuclear material.

South Africa received a significant amount of tritium in a nuclear exchange with Israel where it provided natural uranium.[9] South Africa received four full cylinders in 1977, which contained almost 20 grams of tritium. Other than the initial taking of a small sample, the PNE program (or subsequent nuclear weapons effort) did not use any of this tritium in developing thermonuclear or boosted weapons. Nonetheless, in anticipation of using the tritium in the PNE program, the AEB built a tritium handling laboratory, called the Gas Laboratory, on the main site (Building P1600). It was completed in about 1981.

The actual work on thermonuclear or boosted weapons during the 1970s was minimal. The priority remained the development of a gun-type device.

Initial Gun-Type Designs

By 1976 the AEB had completed the design of a full-size device that was 4.4 meters long, 0.61 meters in diameter, and weighed 3,450 kilograms. The first device was designed to be tested underground in conjunction with extensive instrumentation to learn more about nuclear explosives.

As discussed later, in 1977 South Africa realized that a full-scale underground PNE test would be impractical. Yet, the program had also realized that such a test was not needed in any case. The Reactor Development Division turned to designing a new, smaller design. The second device, finished in 1978, was two meters in length and 0.360 meters in diameter, and it had a mass of 750 kilograms, or about half the size and almost one-fifth the weight of the first device. According to Slabber, in 1978 his team conducted a cold test of this design using natural uranium instead of highly enriched uranium.[10]

The program still did not have enough HEU and would need another year to accumulate the required amounts. After South Africa did so in 1979, it completed the dragon test in Building 5000 and final criticality tests in Building 5200. Afterwards, it assembled its first nuclear explosive device in November 1979 in Building 5200 using about 56 kilograms of about 80 percent HEU. The Y Plant was still not able to make weapons-grade, or 90 percent enriched, uranium. The theoretical group estimated that the explosive yield would be about six kilotons. This yield was somewhat less than half of the yield of the gun-type bomb that destroyed Hiroshima in 1945 but contained a similar amount of about 80 percent HEU.

The South African effort to build a working, gun-type device took about eight years to accomplish. The relatively long development time, however, resulted primarily from the

[9] *Israeli Friends: Secret South African-Israeli Nuclear Cooperation* (Washington, D.C.: Institute for Science and International Security, May 1, 1994). http://isis-online.org/uploads/isis-reports/documents/Israeli_friends.pdf See also "Tritium Programme," op. cit.

[10] Timothy McDonnell, "International Conference: the Historical Dimensions of South Africa's Nuclear Weapons Program" (Washington, D.C.: The Wilson Center, January 4, 2013). https://www.wilsoncenter.org/article/international-conference-the-historical-dimensions-south-africas-nuclear-weapons-program

difficulty South Africa experienced in getting its uranium enrichment plant to produce sufficient amounts of highly enriched uranium for its first nuclear explosive device. The actual time needed to develop and prove a gun-type device was considerably less. In fact, by the time there was enough HEU, the device had been miniaturized.