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A TECHNICAL RETROSPECTIVE OF THE FORMER SOUTH AFRICAN NUCLEAR WEAPON PROGRAMME

ROBERT E. KELLEY

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Signalistgatan 9
SE-169 72 Solna, Sweden
Telephone: + 46 8 655 9700
Email: sipri@sipri.org
Internet: www.sipri.org

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Preface

The story of the South Africa's nuclear weapon programme is unusual because it has a beginning and an end. It is the only country that has actually produced military nuclear weapons and then given them up—voluntarily.

South Africa carried out the programme in secret and dismantled it in secret. But that is not to say it was a very big secret. In the 1980s and into the 1990s most analysts, both governmental and non-governmental, assumed that the programme existed. The first official indication of a weapon programme was the stockpile of hundreds of kilograms of weapon-grade uranium that was declared when South Africa eventually signed the 1968 Non-Proliferation Treaty, in 1991. But it was not until March 1993 that President F. W. De Klerk admitted the existence of the programme and invited the International Atomic Energy Agency (IAEA) to visit and verify the truthfulness of South Africa's declaration.

Many articles and books have been written about the political scope of the programme and the timelines. Until now there has never been a thorough and complete dissection of the technical aspects of the weapons. Robert Kelley has now produced a detailed report on the weapons themselves, the people who produced them, and their successes and failures. Kelley, an experienced nuclear weapon engineer from the United States' own nuclear weapon programme, was a key member of the IAEA team that investigated the scope of South Africa's programme.

In this volume he delves into the technical details of the programme and shows how mechanical engineers, physicists, government policymakers and the military often worked at cross purposes to produce nuclear weapons that had no purpose and were not delivered on time. He has produced a fascinating read from the perspective of a knowledgeable insider. It will stand as a landmark summary of the apartheid nuclear weapon programme.

Dan Smith
Director, SIPRI
Stockholm, October 2020

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Abbreviations

AEB	Atomic Energy Board
AEC	Atomic Energy Corporation
Armscor	Armaments Corporation of South Africa
AVLIS	Atomic vapour laser isotope separation
CNC	Computer numerically controlled
EOS	Equation of state
FXR	Flash x-ray
IAEA	International Atomic Energy Agency
IRBM	Intermediate-range ballistic missile
MLIS	Molecular laser isotope separation
NPT	Non-Proliferation Treaty
PAL	Permissive Action Link
PBX	Plastic-bonded explosive
PMP	Pretoria Metal Pressings
PNE	Peaceful nuclear explosive
RDD	Reactor Development Division
RDX	Hexogen explosive
SADF	South African Defence Force
SAFARI	South African Fundamental Atomic Research Installation (reactor)
SAM	Surface-to-air missile
SQ	Significant quantity
TATB	Triaminotrinitrobenzene
TNT	Trinitrotoluene
UCOR	Uranium Enrichment Corporation of South Africa
UN	United Nations

Elements and units

cm	Centimetre
kg	Kilogram
km	Kilometre
kt	Kiloton (the yield of a bomb expressed as equivalent to thousands of tons of TNT)
mm	Millimetre
Cl	Chlorine
D	Deuterium (hydrogen-2)
F	Florine
H	Hydrogen
HEU	Highly enriched uranium
Li	Lithium
T	Tritium (hydrogen-3)
U	Uranium

Summary

In 1993 South Africa revealed the existence of a nuclear weapon programme that had been dismantled and destroyed. It had built one demonstration device, five complete devices and one unfinished device. After South Africa declared the existence of the programme in 1993, a team from the International Atomic Energy Agency (IAEA) visited the programme's sites in South Africa. While the team was able to confirm the correctness of South Africa's declarations, the IAEA did not document this process and has lost most of the day-to-day records. This account fills some of the gaps that remain in the history of the South African nuclear weapon programme. Much of this report is based on the author's direct experience as the only member of the IAEA team with clearance to examine the nuclear designs of South Africa's gun-assembled and implosion weapons.

The completed devices were all simple gun-type devices, designed to be interchangeable between an aircraft-carried glide bomb gravity bomb and a missile re-entry warhead. South Africa expected a yield of 14–19 kilotons. However, their yield was not a specified military characteristic—a striking omission given that the military needs to plan an engagement, but safety and security were paramount to military and government officials. The highly enriched uranium (HEU) for the weapons was produced using the Helikon stationary enrichment process that was energy intensive, inefficient and used dangerously large amounts of hydrogen.

Throughout the programme there were several main players: the Atomic Energy Board (AEB), the Armaments Corporation of South Africa (Armscor) and the South African Defence Force (SADF).

The AEB was run by civilians—largely scientists and nuclear engineers, whose approach to the problem was scientific. It was responsible for the programme's early work at the Somchem ammunition plant near Cape Town and the Pelindaba nuclear research centre near Pretoria to produce HEU and the first gun-type devices. However, its poor security precautions for a planned nuclear test in 1977 caused the government extreme embarrassment.

Armscor, a state-owned arms manufacturer, designed and built the Circle facility in 1979–80 under the management of Kentron, a military contractor. The Circle staff were mechanical and aerospace engineers. While they understood reliability, quality, manufacturing and security, they did not understand physics. After the government decided in 1985 to end the nuclear weapon programme once the seven gun-type devices on the production line had been completed, Armscor then devised an implosion weapon programme at a new site called Advena. However, this suffered from most of the same military and political disadvantages as the gun-type programme.

Throughout, the SADF seemed reluctant to embrace the programme. A lack of military requirements in programme documentation suggests that it was not very involved. While the programme was conceived in the context of a long-running war with neighbouring states, the nuclear weapons were unsuited for this conflict. Two prototype nuclear devices were produced in 1979 and 1982, but a

serious safety defect in the mechanical design meant that the programme failed to deliver a single usable device during the critical years 1982–88. Most of the usable weapons were completed in 1988 and 1989.

While the Pelindaba and Advena facilities have been credited with most technical responsibility for the programme, the Somchem facility was a key supplier of gas centrifuge technology and was left with a larger reserve of technology. The former two facilities continued to support activities related to gas centrifuge enrichment even after the weapon programme ended. Circle was hot pressing samarium–cobalt magnets in 1993 of a size and strength used in uranium enrichment centrifuges, and probably well before. This activity may have directly benefited the activities of the A. Q. Khan proliferation network.

Abdul Qadeer Khan was a Pakistani metallurgist who built a uranium enrichment program in Pakistan using gas centrifuge technology he stole from the Netherlands in 1974. A very important part of Khan's contribution to Pakistan's nuclear weapons program was building a network of mostly European suppliers for critical technology and materials not available in Pakistan. Once Pakistan achieved self-sufficiency in centrifuge manufacturing, Khan reversed his network of suppliers and used it to supply several other proliferating countries with centrifuge enrichment technology. They became known as the A.Q. Khan proliferation network. The network supplied classified information and materials to Iran, Libya and possibly other countries. In particular, Khan supplied Libya with drawings and instructions on how to build an actual nuclear explosive device.

1. Introduction

The nuclear weapon programme of South Africa stands out from other national programmes in its unorthodox organization and lack of focus. For about 20 years the programme moved in fits and starts, lacking direction. Eventually it produced a small stockpile of seven nuclear devices that had little purpose and little governmental or military support. Only five of the devices could be counted as 'weapons'. One device had no weapons features and could only be placed underground for a nuclear test demonstration. The seventh device was never fully completed. This report documents the evolution and demise of the programme from a technical point of view. Internal conflict, indifference and confusion, coupled with technical problems, doomed the programme to failure. This was a good outcome from the point of view of nuclear non-proliferation.

Many histories have been written about the South African programme. It is necessary to repeat some of that history for context. But the real purpose of this review is to look at the programme's technical accomplishments and failures. Many of the verification lessons that were learned stand to be lost and there are few resources left to document them three decades later.

In 1993 the South African Government invited the International Atomic Energy Agency (IAEA) to visit the sites of its former nuclear weapon programme. That government expected elections and the end of apartheid, and it wanted to leave a clear record of past nuclear ambitions. The government was seeking outside verification that a former weapon programme had been dismantled and that nuclear materials from that programme had been completely diverted to non-military purposes.

The visits had two main elements. One, consisting of about a dozen people, studied material records and made measurements of uranium compounds to establish a material balance consistent with the claim that all materials were accounted for. The second element was verification of the weapons themselves to establish consistency with the findings of the materials team. The IAEA expected that South Africa was planning to provide nuclear weapon design information to aid in the resolution of past activities. Since IAEA employees should not gain knowledge of nuclear explosive design as a consequence of IAEA employment, this element had to be undertaken by an IAEA employee from a nuclear weapon state who had nuclear weapon clearance in their home state.[1] There was only one such IAEA employee: the present author. Other IAEA employees provided support while visiting and dissecting the programme's sites and equipment, but they did not examine the nuclear designs of South Africa's actual gun-assembled and conceptual implosion weapons.

[1] Statute of the International Atomic Energy Agency, approved 23 Oct. 1956, entered into force, 29 July 1957, as amended up to 28 Dec. 1989, Articles II, III.A.5 and III.B.1; and Treaty on the Non-Proliferation of Nuclear Weapons (Non-Proliferation Treaty, NPT), opened for signature 1 July 1968, entered into force 5 Mar. 1970, IAEA INFCIRC/140, 22 Apr. 1970.

Box 1.1. The records of the International Atomic Energy Agency visits to South Africa in 1993

At the time that South Africa asked the International Atomic Energy Agency (IAEA) to send a team to try to confirm that its nuclear weapon programme had existed and had been destroyed, the agency was carrying out inspections of Iraq's newly discovered nuclear weapon programme. The IAEA Director General designated a team made up of the same IAEA employees who were inspecting Iraq to carry out the visits to South Africa.

The Iraq inspections were directed from outside the IAEA, largely by the United Nations Special Commission (UNSCOM) and the United States Government. The IAEA was determined to carry out the task in South Africa entirely on its own and retain control of all findings. All materials, reports, photographs and detailed records and findings were held within the IAEA Department of Safeguards. Summary conclusions were released but with little detail. Unlike the Iraq inspections, the detailed findings of the South African visits were not shared with any member state.

The Director General made it clear to all team members that records were to be centralized at the IAEA. Member states were not to be kept informed. Although most team members were encouraged by their member states' ambassadorial delegations to share their findings (with inducements such as fine dining), all records were turned in to the team leader.[a] They were kept under lock and key, where they were inaccessible and eventually lost. The failure to involve member states also meant there was no secondary repository of the knowledge gained in the visits.

In later years there were efforts to find and document the detailed findings and procedures used by the 1993 teams. In 2004 virtually none of the detailed records, photographs and supporting material could be located. Offices had moved several times, people had retired and records were lost. Some of the records were found in 2008 but were destroyed by a file clerk in 2009 before they could be saved for posterity.

Many authors have written about the South African nuclear programme, all without the benefit of the detailed records. Fortunately, this author has retained a great deal of personal knowledge and has used that information to reconstruct the programme in much more detail than is otherwise possible.

[a] Following the first visit in 1993, the present author sent a short note to the US ambassador to the international organizations in Vienna, Jane Becker, that the process was working well and would probably be completely successful. The note was returned by the US Mission noting that there was to be no correspondence on this highly secret enterprise. And in place of fine dining was a visit to the IAEA cafeteria, Dutch treat.

The IAEA did not document this process and did not retain most of the records related to daily visits, the sites visited, photographs, literature and supporting documents (see box 1.1). In the absence of these details, the IAEA has little in terms of historical record that would help to assess a similar situation in the future.

While other authors have documented the South African programme, this account has been written to fill in the many gaps that remain in the historical narrative of what South Africa did and when. In particular many details examined in this report help to answer questions of why South Africa did certain things and whether or not these efforts were successful. The approaches taken by South African scientists and engineers were quite different from the directions taken by a number of other successful states. The differences were so great that they stand out clearly even today. The analysis here fills in many of the gaps from the current public record in the hope that a permanent historical record will be complete for future non-proliferation analysts.

Much of this report is based on the author's direct experience. Whenever possible, corroborating references to other sources are given in the footnotes. But in many cases the present author is the only person who examined or analysed the technical details that are described here. These descriptions build on earlier publications, sometimes highlighting the significance of something that has been previously overlooked and, in some cases, contradicting other sources.

This introduction continues with a brief account of the development and progress of the programme and the IAEA visits that followed its closure (see also the timeline in the appendix). The following chapters then look at each of the significant sites of the South African programme in turn. The sites that were significant for the early steps and for the development and testing of the gun-type weapons were the Somchem plant (chapter 2), the Vastrap test site (chapter 3), the Pelindaba site (chapter 4) and the Circle facility (chapter 5). After a diversion to consider lithium isotope separation and the tritium program at Pelindaba (chapter 6), the volume moves on to the development of implosion devices at the Circle and Advena facilities (chapter 7), and the other sites of interest (chapter 8). It ends with a brief description of how the programme was closed down (chapter 9), followed by conclusions and key findings (chapter 10).

A brief history of the South African nuclear weapon programme

The South African nuclear weapon programme was conceived in the apartheid era by politicians and senior staff of the Atomic Energy Board (AEB) and its successor, the Atomic Energy Corporation (AEC or, in Afrikaans, AEK). Like many other developing countries in the 1960s and 1970s, South Africa was interested in producing electrical power from nuclear energy. What made South Africa unique among such countries was that it also had its own considerable resources of uranium, largely as a by-product of mining other minerals. Thus, not only could South Africa produce nuclear energy from its own uranium, it could also export uranium to other countries. Moreover, value could be added to the exports by enriching the uranium to power reactor levels before sale. Thus, the South African enrichment programme was born.[2]

The Uranium Enrichment Corporation (UCOR) was established in 1970. From this time South Africa came under increasing military threat from its north. The Border War over secession of South West Africa (which eventually gained independence as Namibia) also involved the South African Defence Force (SADF) in the Angolan War of Independence and, from 1975, the subsequent Angolan Civil War. At first South Africa prevailed in a largely open-country guerrilla war but in time Angola, backed by Cuba, backed in turn by the Soviet Union, began

[2] For a general history see e.g. Fig, D., 'Nuclear energy rethink? The rise and demise of South Africa's Pebble Bed Modular Reactor', Institute for Security Studies (ISS) Paper no. 210, Apr. 2010; and Steyn, H., van der Walt, R. and van Loggerenberg, J., *Armament and Disarmament: South Africa's Nuclear Weapons Experience* (Network Publishers: Pretoria, 2003).

to prevail and potentially threaten the South African heartland. This situation escalated continuously until 1989. In 1974 secret plans were drawn up for the AEB to develop a nuclear device that could be weaponized and used in the looming conflict.[3] Using highly enriched uranium (HEU) from the AEB's Pelindaba complex near Pretoria, the first steps to construct a gun-type nuclear device were taken at the Somchem plant near Cape Town. To illustrate the seriousness of the project, plans were drawn up to conduct a nuclear test at Vastrap in the Kalahari Desert.[4] The test was approaching readiness in 1977 when it was scrapped after preparations were detected by both the Soviet Union and the United States.[5]

The central government was greatly embarrassed by this security lapse by scientists unused to military security. It made arrangements to transfer the weapons portion of the programme away from the AEB. The Armaments Corporation of South Africa (Armscor), a state-owned arms manufacturer, contracted Kentron, a military contractor associated with small airframes, weapons and defence, to take over the programme. It built a new facility called Circle several kilometres away from Pelindaba. This facility became active around 1980 under a stricter security and operations culture.

In about 1982 a dummy military test revealed a serious safety defect in the mechanical design of the gun-type bomb that was being weaponized.[6] Progress on building devices ground to a halt. From 1982 to 1988 no complete devices were produced while mechanical faults were re-engineered.[7] The significance of this gap is huge. It has been covered up or ignored in other histories. In the mid-1980s the war in Angola continued to go badly for South Africa: SADF aircraft were virtually confined within the borders of South Africa for fear of being shot down by Soviet-made surface-to-air missiles (SAMs). The time taken to fix the bomb defect is a clear sign that nuclear weapons were not vital to the war effort. There was little strategic sense in having only a few usable bombs that could be used against Cuban troops attacking in open savannah or rangeland. Using a nuclear weapon in such a case would be militarily ineffective yet a serious escalation for a country with a small nuclear reserve and, furthermore, would make South Africa a pariah state for using nuclear weapons for the first time since World War II.

Perhaps recognizing this, in 1985 the South African Government decided that the nuclear weapon programme would end once the seven gun-type devices produced at the Circle facility had been completed.[8] However, also in 1985

[3] Stumpf, W., Atomic Energy Corporation of South Africa, 'Birth and death of the South African nuclear weapons programme', Presentation at the conference '50 years after Hiroshima', Castiglioncello, Italy, 28 Sep.–2 Oct. 1995, section 3.

[4] E.g. Pabian, F. V., 'South Africa's nuclear weapon program: Lessons for US nonproliferation policy', *Nonproliferation Review*, vol. 3, no. 1 (fall 1995), pp. 1–19.

[5] Bidgood, S., 'The 1977 South Africa nuclear crisis', eds W. C. Potter and S. Bidgood, *Once and Future Partners: The United States, Russia and Nuclear Non-proliferation* (International Institute for Strategic Studies: London, 2018).

[6] For a detailed description of the defect and its impact on the programme see Albright, D. with Stricker, A., *Revisiting South Africa's Nuclear Weapons Program: Its History, Dismantlement, and Lessons for Today* (Institute for Science and International Security: Washington, DC, June 2016), p. 110.

[7] Albright with Stricker (note 6).

[8] Stumpf (note 3), section 4.

Armscor obtained funding for a new programme to develop uranium implosion devices, which would use HEU much more efficiently than gun-type devices. The Advena Central Laboratories, not far from the Circle facility, were largely built between 1986 and 1988 for this new mission. This counterproductive effort is a key part of the enigma of the failed programme.

Political statement of the programme

The purpose of the South African nuclear weapon programme was largely political. The actual military use of the few weapons was a remote possibility. As stated by the government on numerous occasions, the programme had three planned phases.[9] Phase 1 was to create and maintain uncertainty about whether South Africa even had nuclear weapons, based on the assumption that such ambiguity itself would function as a deterrent. Phase 2 was to make the capability known by declaring it to the USA. This would provide South Africa with leverage over the USA. Moreover, if the USA knew, then the story would certainly leak, enforcing the deterrent effect. Phase 3 would be to carry out an underground test to prove capability. This plan was still in effect in 1988, when Armscor had the desert test shaft at Vastrap renovated, even though it was no longer secret and was under observation by Soviet and US satellites.[10]

It is interesting to note that these were all political options stated by the civilian government, but there was no mention of a military mission. Clearly, it is convenient after the fact to not mention that these were awesome weapons of war. High-level South African hosts working with the IAEA also made it clear that abrogation of agreements by the USA and sanctions pushed South Africa to adopt an independent foreign policy, to innovate and to lose trust in the USA. For example, the USA abrogated its fuel-supply agreement for the SAFARI-1 (the South African Fundamental Atomic Research Installation) reactor in 1977.[11]

The end of the programme

In 1989 F. W. de Klerk replaced P. W. Botha as South African State President. He quickly decided to dismantle the nuclear weapon programme and the SADF did not object.[12] A ceasefire had taken effect in the war in Angola. South Africa was suffering from international trade sanctions and an arms embargo. Apartheid was apparently about to collapse.

De Klerk proceeded to try to keep the programme secret while the HEU was removed from the weapons, melted down and returned to the AEC. After this was completed in early 1991, South Africa acceded to the 1968 Treaty on the Non-

[9] Stumpf (note 3).

[10] Stump (note 3), section 4.

[11] Vlok, J. W. H., South African Nuclear Energy Corporation (NECSA), 'Reactor operations at Safari-1', Presentation, 9th Meeting of the International Group on Research Reactors (IGORR), Sydney, 24–28 Mar. 2003.

[12] Stumpf (note 3), section 4.

Proliferation of Nuclear Weapons (Non-Proliferation Treaty, NPT) on 10 July 1991. Two years later, de Klerk revealed the programme in a speech to the South African Parliament on 24 March 1993 and simultaneously informed the United Nations and the IAEA.[13] South Africa declared all of the HEU to the IAEA and accepted safeguards on the material. Eyebrows were raised at the sudden disclosure of so much HEU, but South Africa was under no obligation to say where it had come from.[14]

IAEA transparency visits in 1993

At the time that South Africa declared its dismantled weapon programme, two IAEA inspectors were in the country. The following day, 24 March 1993, they performed a perfunctory visit, including a short briefing by the South Africans.[15]

Three major visits took place in 1993: 23 April–3 May, 7–11 June and 10–13 August.[16] Teams of about 12 people carried out the visits. The team compositions varied slightly but there was continuity.

Most of the IAEA staff in each visit focused on accounting for the nuclear material that South Africa had declared and on a careful reconstruction of knowledge of the South African enrichment programme. This process of nuclear material accounting could then be used to establish the consistency of historical declarations with claims about the weapon programme. The outcome can be summarized as being satisfactory and generally consistent with South Africa's declarations and measurements of nuclear materials declared and verified by IAEA.[17]

The rest of the team attempted to map out the full scope of the declared but dismantled weapon programme. This included learning about the nuclear designs, accounting for materials including specialized non-nuclear materials such as tungsten, discovering and visiting all of the weapon programme's sites, understanding technology, assessing plans for future activity (whether conducted or not), and validating that all weapons that had been built had been destroyed or rendered harmless.[18]

This mapping activity was a security problem for the IAEA. The IAEA had few employees on its staff with complete nuclear weapon clearances from their home state. In practice, as noted above, there was only one: the present author, with

[13] de Klerk, F. W., South African State President, 'Nuclear Non-Proliferation Treaty', Speech to a joint session of Parliament, 24 Mar. 1993; and 'The dismantlement of South Africa's nuclear weapons', South African History Online, 31 Mar. 2011.

[14] E.g. von Baeckmann, A., Dillon, G. and Perricos, D., 'Nuclear verification in South Africa', *IAEA Bulletin*, vol. 37, no. 1 (Mar. 1995), pp. 42–48; and Kerr, P., 'Lessons learned From denuclearizing states', *Arms Control Today*, vol. 49, no. 4 (May 2019).

[15] von Baeckmann et al. (note 14).

[16] International Atomic Energy Agency, Board of Governors, 'The agency's verification activities in South Africa', Report by the Director General, GOV/2684, 8 Sep. 1993, annex 1.

[17] von Baeckmann et al. (note 14).

[18] Heinonen, O., 'Verifying the dismantlement of South Africa's nuclear weapons program', ed. H. D. Sokolski, *Nuclear Weapons Materials Gone Missing: What Does History Teach?* (US Army War College, Strategic Studies Institute: Carlisle Barracks, PA, Nov. 2014), pp. 163–84.

weapon clearance from the USA. The IAEA and the South Africans agreed to let that one employee conduct all interviews in South Africa where design details were revealed. During the June visit a Russian contractor with appropriate clearance assisted with some of the weapon assessment.

Team members from non-nuclear weapon states assisted in the physical inspection of weapon sites, equipment and materials in which nuclear weapon design was not revealed. This arrangement was largely satisfactory to both the IAEA and South Africa, although some individuals from non-nuclear weapon states aggressively attempted to elicit information on nuclear weapon design.

Equally, the US inspector was bound not to share weapon design information with the IAEA. To complete the mission, that inspector—this author—prepared a statement about his weapons findings for the IAEA Director General and summarized findings without going into design details.

Transparency visits, not inspections

The 1993 visits were not inspections in a legal sense. The activities that South Africa declared had been conducted before it acceded to the NPT and so were not prohibited. Hence, South Africa voluntarily invited the IAEA to verify the dismantlement and destruction of its nuclear weapons as a transparency measure. This was not legally required, but since the end of apartheid was evidently only a year or two away, with a radical shift in government, the government at the time felt an independent review was prudent.[19]

In this report the term 'inspector' and 'inspections' are used as a general description of the process of carrying out the verification. Inspector is a valid term for the activities, but it does not mean 'inspector' as defined in normal agreements between the IAEA and states. Moreover, the term 'auditor' is not used because it carries too great a connotation of authority and responsibility to correct misstatements or errors. The inspectors were only allowed to observe and make reports on what they saw.

Interactions between the state and the IAEA

Initially the interactions between the two parties were tense. The majority of inspectors in the IAEA team were from the Iraq Action Team, which since May 1991 had been removing and destroying nuclear-related material and equipment in Iraq. After working in Iraq for almost two years, these inspectors were used to obfuscation, lying and interference. They were prepared for the same non-cooperation from their South African counterparts.

The South African side had been watching the progress of the IAEA inspections in Iraq. The Iraq inspections had been confrontational, as could be seen in the press and in the UN Security Council. The IAEA had destroyed many buildings in Iraq and supervised the destruction of specialized equipment worth millions of dollars. The South Africans did not want to be treated in the same way.

[19] von Baeckmann et al. (note 14).

Box 1.2. Special limitations on inspectors

South Africa imposed two limitations on the International Atomic Energy Agency (IAEA) inspectors.

1. The IAEA could not investigate foreign sources for the supply of materials and information used in the programme. This included equipment, documentation, computer codes, materials and foreign expertise in South Africa. The reason was that South Africa was under sanctions and many of the activities that could be disclosed could lead to prosecutions of people and companies still in South Africa, under international law.[a]

2. The IAEA could not have access to, or ask questions about, the military delivery systems that were used or might be used for the nuclear weapons. This could have led to disclosure of conventional military capabilities. It is important to remember that South Africa had just reached a ceasefire in the costly war in Angola and was sensitive to a renewed threat.

[a] UN Security Council Resolution 418, 4 Nov. 1977.

Fortunately, each side quickly accepted the other, and within a day or two it became clear that the process could be cooperative and transparent.[20] South Africa provided exceptional access to people and facilities associated with the programme and even granted access to other sites to establish that they were not involved in the programme and hiding undeclared capabilities.[21]

South Africa generally agreed to allow visits to any facility requested by the IAEA. The IAEA was to have full access to people for interviews and to most records. Two exceptions were agreed in advance (see box 1.2).[22] These two restrictions were largely observed. They did not generally inhibit successful outcomes and were occasionally breached in private conversations.

Every indication is that the IAEA was satisfied that South Africa had made a complete declaration of its former programme.[23] At that moment it could be truly stated that South Africa was the first and only country known to have built nuclear weapons itself and to have voluntarily destroyed them.[24]

[20] International Atomic Energy Agency, GOV/2684 (note 16); Kerr (note 14); and von Baeckmann et al. (note 14).

[21] Stumpf (note 3).

[22] 'South Africa's nuclear autopsy', Wisconsin Project on Nuclear Arms Control, 1 Jan. 1996.

[23] US Department of State, Bureau of Intelligence and Research, 'South Africa: Nuclear case closed?', 19 Dec. 1993 (redacted).

[24] Stumpf (note 3), section 9.

2. The Somchem plant

Although the nuclear programme had its origins at the Somchem ammunition plant at Somerset West near Cape Town, by 1993 this site had no known ongoing connection to the mainstream nuclear weapon programme. Nonetheless, the South African authorities agreed to visits to the historical sites and other sites of interest to the IAEA.

Historically, researchers have tended to focus on the Armscor and AEC activities near Pretoria. That was where the actual weapon programme took place. In terms of capabilities for a future South African programme, especially implosion weapons, Somchem is far more interesting. It has the materials, test facilities, diagnostics, computer codes, hydrodynamicists and experienced personnel to quickly build a programme. In the period around 1987, the new Advena project and laboratory were trying to develop all of these capabilities using mechanical engineers and they would have taken years to do this. Lastly, Somchem was even involved in advanced uranium enrichment.

When UCOR was established in 1970, a subsidiary goal was production of a nuclear explosive. In 1974 work was approved to develop a nuclear explosive at Somchem. The initial stated goal was to produce a peaceful nuclear explosive (PNE) for mining applications.[25] A PNE can be used to fracture large rock bodies to make them easier to mine or to make extraction of oil and gas easier.[26] This technology was pursued extensively by the USSR in the 1970s and the USA's Project Plowshare had a similar goal.[27] In general, PNE is now a discredited technology—the downsides of the idea of blasting a canal across Nicaragua with nuclear explosives are now apparent—and PNEs would be banned under Article 1 of the 1996 Comprehensive Nuclear-Test-Ban Treaty (CTBT).[28] However, at that time a South African PNE programme could have been credibly justified for mining. It is also likely that senior AEB officials had militaristic ambitions even at this early stage. For example, construction of the first nuclear test shaft at Vastrap in the Kalahari Desert in the northern Cape was approved in 1974.[29]

Early experiments at Somchem were carried out to develop a propellant and barrel system for a conceptual gun-type device (see box 2.1). Projectiles were initially just fired into a bed of sand in building T25 at Somchem. The first results produced a device that used a 2-metre-long piece of naval gun barrel and a projectile that weighed about 50 kilograms (including tamper pieces). The goal was to bring the pieces together at 300 metres/second—any faster than this would have required a really strong bomb casing and any slower might have led to the

[25] Nordyke M. D., *The Soviet Program for Peaceful Uses of Nuclear Explosions*, UCRL-ID-124410-Rev-2 (Lawrence Livermore National Laboratory: Livermore, CA, 1 Sep. 2000), p. 12.

[26] Stumpf (note 3), section 3.

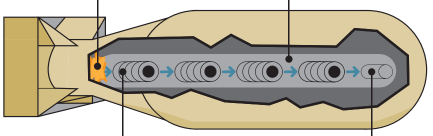
[27] CTBTO, 'Peaceful nuclear explosions'.

[28] Comprehensive Nuclear-Test-Ban Treaty (CTBT), opened for signature 24 Sep. 1996, not in force.

[29] Gould, C., 'The nuclear weapons history project', ed. K. Allan, *Paper Wars: Access to Information in South Africa* (Wits University Press: Johannesburg, 2009), pp. 88–121, p. 107; and Stumpf (note 3), section 3.

Box 2.1. Gun-type weapons

Gun-type weapons work by propelling two subcritical masses together to produce a supercritical mass and hence a nuclear explosion.[a] The joining of the subcritical masses must be done quickly for nuclear physics reasons. Hence, the first gun-type weapon used at Hiroshima, Little Boy, used gunpowder to propel one piece of uranium down an old naval gun barrel against another piece.



Simplified schematic from the internet of the US 'Little Boy' nuclear bomb, to which the South African device was similar

Gun-type weapons are basically separated into two parts, a fairly massive static subcritical mass called the front end, and a smaller uranium projectile fired down the gun barrel into the mass.[b] The projectile, with some tungsten tamper sections at the front and back, is called the back end. Some military devices, such as Little Boy, actually fired massive rings of uranium over a projecting cylinder of uranium. The concept is the same, but this was not the South African approach.[c] The back end of the South African bomb had many moving parts and interlocks.

Gun-type weapons are fairly easy to design, easy to test in a non-nuclear fashion and simple to build. They do not compress nuclear material beyond room density. Hence, they are inefficient and expensive to build in terms of quantities of highly enriched uranium (HEU). They are considered today to be crude and are probably not in any country's weapon stockpile. Nevertheless, South Africa had a robust uranium-enrichment capability, plenty of uranium feed material, plans for a small nuclear weapon stockpile and little need for haste. Gun-type weapons were its initial and only successful project.

A final reason for choosing gun-type weapons is that there is wide agreement that they do not need a nuclear test for confidence. They are simple, easy to calculate and easy to verifiably test without an explosion. For example, the Hiroshima bomb was never tested before it was used in combat in 1945. South Africa wanted the option of having ambiguity and deniability. The requirement to have a nuclear explosion test of an implosion bomb was not consistent with this goal.

[a] Coster-Mullen, J., *Atom Bombs: The Top Secret Inside Story of Little Boy and Fat Man* (John Coster-Mullen: Waukesha, WI, 2014).

[b] Rhodes, R., *The Twilight of the Bombs: Recent Challenges, New Dangers, and the Prospects for a World Without Nuclear Weapons* (Alfred A. Knopf: New York, 2010), p. 160.

[c] See e.g. Coster-Mullen (note a).

device being pre-initiated by a stray neutron or cosmic ray and not exploding. This device was too large and too heavy to be a deliverable weapon and was large even for a mining explosive. Nevertheless, a 'cold' version of this device—using natural, non-fissile uranium—was the first candidate for a dry run of a nuclear test at Vastrap in 1977.

The Somchem armaments factory is a sprawling military factory. The main function of the site is armaments and missile production.[30] In the 1970s it would have been a logical place to begin a new weapons programme. Its high-explosive capabilities were quite ordinary. For example, Somchem could cast explosives but had no capability for isostatic pressing—a process for producing materials with uniform density and microstructure by applying equal pressure in all directions to a powder compact. Missile activities were severely cut back by US missile inspection teams around 1994 in response to South Africa's abandonment of its long-range missile and nuclear programmes.[31] For example, pits in the ground where South Africa had been casting large solid missile motors had been partially filled with concrete so that only small rockets could be produced in the future.

At the time of the IAEA visits in 1993, the historical sites where the first nuclear devices were developed were of little interest to inspectors because everything had been destroyed and the buildings were used for other purposes. The main interest at Somchem was the testing area next to the ocean (at 34.0804° S, 18.7705° E). The testing area had excellent diagnostics for measuring high-explosive events such as penetration of armour by shaped charges and formation of jets (see below). The test area was heavily armoured with railroad ties and steel mesh netting to prevent shrapnel damage. This was a high-quality site dedicated to long-term use. The firing limit for the site was 5 kg of high explosive with a storage area for 7 kg. This was a sophisticated site with technologies of direct interest to an implosion nuclear weapon programme. Therefore, it was of interest to inspectors and needed to be examined for evidence of ties to a nuclear weapon programme.

The equipment used at Somchem testing area was excellent. It was inventoried during the IAEA visits but there was no basis for removing it because there was no link to nuclear weapons. However, the inspectors discovered that the Somchem team had been investigating depleted uranium as an amour penetrator and as a liner for a shaped charge. This came as a surprise to the Department of Foreign Affairs and to a guide from Armscor—they had no knowledge of this kind of activity and were greatly embarrassed. It turned out that the AEC at Pelindaba had been casting and machining uranium alloys for this small programme without the knowledge of higher authorities and without nuclear material safeguards. The AEC only kept records on enriched uranium and not on natural or depleted material.

Uranium shaped charges were not tested at Somchem. They were tested on a military range at Alkantpan (see chapter 8).

Shaped charge development

Shaped charges use conventional high explosives to impart focused energy to metal liners that can penetrate more deeply into hard materials than projectiles or high explosives alone. Their development shares a lot of technology in common with

[30] Rheinmetall Defence, 'Rheinmetall Denel Munition (Pty) Ltd', [n.d.].
[31] 'South Africa's nuclear autopsy' (note 22).

implosion weapons. Hydrodynamic codes are similar, the size of experimental items can be similar and they use some of the same materials.

Implosion diagnostic development is particularly important. The best diagnostics for shaped charges were at Somchem and the Naschem ammunition plant (see chapter 8) with proof testing at Alkantpan. Naschem declared some work with shaped charges. This was limited to light metals and had excellent diagnostics: flash x-ray (FXR) and fast cameras. High-speed cameras can take thousands of frames of images per second. A researcher can actually see an explosive charge blowing up in many frames. FXR cameras can take a single image through an explosion and see metal projectiles penetrating through armour and how their shapes change.

Somchem gave detailed explanations of its work. It improved cone charges that have been around since World War II and have been experimentally studied for years. The main task at Somchem was to try new models and make measurements of their ability to penetrate buildings and armour.

The most interesting work at Somchem involved the use of hemispherical shells in high explosives instead of World War II-era cones. Cones had been developed by trial and error, but hemispherical shells needed hydrodynamic computer code design to be effective. Somchem was running such codes and doing high-technology diagnostic experimentation at its beach-front facility at Somerset West. Diagnostics included FXR systems from a US commercial supplier and high-speed cameras of many kinds. FXR diagnostics were on photographic film, rather than image intensifiers. A special class of hemispherical shaped charge was developed at Somchem that did not use a constant wall-thickness hemispherical metal shell in the charge. Instead, this so-called P-charge used a specially shaped hemisphere that was thicker at the pole than at the waist. This required computer design calculations rather than just trial and error.

Manufacturing the P-change requires good machine tools. A certain mythology has grown up around the use of computer numerically controlled (CNC) lathes or mills in such a case. On the one hand, CNC machines are valuable for producing many complex shapes. They also provide greater quality control and high throughput of parts if there is a lack of skilled machinists. On the other hand, high-quality tracer lathes can make axially symmetrical shapes of revolution such as the P-charge liner. To begin, a CNC machine or a skilled machinist makes one precise template. The much cheaper and simpler tracer lathe then uses the template to control its movements and makes duplicate precise parts. That is what Somchem was doing. The codes and experience for designing P-charges were at the cutting edge for 1990 and were of considerable interest. Somchem also looked at other shapes such as trumpet-bell shaped metal liners. In this regard Somchem was a modern first-class experimental facility. It was far ahead of where Advena was trying to be in hydrodynamic compression design.

An interesting side discussion at Somchem concerned programme security. The Circle implosion design team had been querying Somchem personnel about various hydrodynamic topics and experiments related to implosion and had even published some papers. Two of the Somchem staff correctly discerned that

Circle was working on an implosion weapon and began to speculate publicly. The government brought the Somchem staff in and briefed them on the nuclear programme and muzzled them under the 1956 Official Secrets Act. From that time, Somchem, which was also under the control of Armscor, made efforts to try to wrest control of the implosion weapon programme away from Circle. In fact, from a purely scientific and engineering point of view, this would have been a good move. The Somchem staff were experienced professionals in the technology, while the Circle staff were learning as they went. But the programme did not last long enough for this drama to play out.

Enrichment support at Somchem

The Somchem hosts were not quite prepared for an IAEA visit in 1993. They put the visitors into a conference room and, to occupy them, showed them a publicity film about the overall mission of the Somchem plant. In the film there was a considerable section devoted to filament winding of cylindrical tubes for missile bodies.[32] This is the exact same technology that is used in many modern gas centrifuges for enrichment. The team began to ask questions about the technology and asked for a site visit to the winding shop. This is one of the few times that South Africa refused an IAEA visit request. The Somchem management left the room and returned with an official from the Department of Foreign Affairs. Gas centrifuges for uranium enrichment were outside the scope of the weapons investigation: the IAEA investigation was limited to the Helikon stationary enrichment process (see chapter 4) and the weapons themselves. In later years the present author learned that South Africa had a promising gas centrifuge programme based on carbon fibre rotor tubes produced at Somchem.

This incident highlights the several opportunities that the IAEA failed to follow-up on the centrifuge programme. The IAEA allowed itself to be largely limited to the obvious: Helikon enrichment and the weapon programme. If the IAEA had been more assertive, it might have been able to examine a major enrichment programme and prevent further proliferation. All of the centrifuge programme hardware and documentation subsequently disappeared, and many South Africans ended up being part of the clandestine nuclear proliferation efforts of Abdul Qadeer Khan.[33] The A. Q. Khan network was responsible for Pakistan's acquisition of nuclear weapon technology, and the subsequent spread of that technology and equipment to other proliferating states.[34]

Also, at Somchem the South Africans invoked the other precondition that the IAEA had agreed to: no information about sources of supply (see box 1.2). The computer codes used for the hydrodynamics of the shaped charges were of great interest. Somchem declined to even identify the codes that it used on the basis that

[32] 'South Africa's nuclear autopsy' (note 22).

[33] Reed, T. C. and Stillman, D. B., *The Nuclear Express: A Political History of the Bomb and Its Proliferation* (Zenith Press: Minneapolis, MN, 2009), p. 184.

[34] International Institute for Strategic Studies (IISS), *Nuclear Black Markets: Pakistan, A.Q. Khan and the Rise of Proliferation Networks—A Net Assessment* (IISS: London, 2007).

they were supplied by a foreign source. This is another indication that Somchem was probably a greater reservoir of advanced knowledge than the groups near Pretoria: the AEC, Circle and Advena.

3. The Vastrap nuclear test site

In 1974, as the Border War escalated, the AEB drew up secret plans to develop a conceptual nuclear explosive device that could be turned into a military weapon and used in the conflict.[35] To illustrate the seriousness of the project, plans were developed to conduct a nuclear test.[36]

After construction of a nuclear test shaft at Vastrap was approved in 1974, geological studies began and construction took place from October 1975 to November 1976. The first shaft was designated PG-1 (PG stands for placing hole in Afrikaans). It was 391 metres deep and 0.9 metres in diameter. A second shaft, PG-2, was constructed nearby from April to November 1976. This was 215 metres deep and 0.9 metres wide. There may have been smaller bore holes for geological studies and diagnostics. The two main shafts were closed around 1988. The drilling equipment came from the mining industry and was purchased from an unspecified European company. It was considered obsolete and sold for scrap after the holes were drilled.

The shafts were not straight, which meant that the nuclear explosive might get stuck during emplacement. Moreover, some diagnostics require a straight line-of-sight to the device. Some remedial work with conventional explosives was required to get a straight shaft. Another problem was that the water table is at a depth of about 120 metres at this location. Emplacing a nuclear test under water introduces many practical difficulties. For example, placing the many high voltage and other wiring cables needed for a complex device deep under water is a difficult challenge similar to constructing a submarine.

A dry run was planned for September 1977. This involved emplacing the first heavy Somchem device at the bottom of the test shaft with all necessary cabling and command input. It can be assumed that the device used depleted uranium because no enriched uranium was available in 1977. There would be minimal diagnostics but the arrangement was planned to be a realistic test exercise, with trailers to control the firing and collect diagnostic data placed at safe distances from the top of the hole.

After all these preparations, the dry run was aborted and the site was evacuated. This came about because a Soviet reconnaissance satellite spotted the drilling activities. The USSR correctly concluded that a nuclear test site was being developed and alerted the USA. Officially the USA was sanctioning South Africa at the time because of apartheid. But the USSR was indirectly prosecuting the war against South Africa by using Cuban troops in the ground war in Angola. The USSR thus left the diplomatic démarches to the USA. According to a South African counterpart, one day in September 1977 a small aeroplane crossed over the site and disappeared. This might have been the US ambassador's aeroplane.[37] By the

[35] Stumpf (note 3), section 3.

[36] E.g. Pabian (note 4).

[37] Burns, J. F., 'South Africa ousts 3 US embassy aides, charging air spying', *New York Times*, 13 Apr. 1979.

Box 3.1. A possible nuclear test in the South Atlantic

A United States Vela reconnaissance satellite detected a flash in the sky over the South Atlantic Ocean on 22 September 1979. The flash exhibited the 'double hump' light flash typical of an atmospheric nuclear explosion that the satellite was built specifically to detect. The US designated this as Event 747.

There was considerable controversy over whether this was a detection of a nuclear explosion or a random event caused by a malfunction of the satellite sensor.[a] There was major international speculation that South Africa had detonated a nuclear device.[b] Despite the fact that the South African nuclear weapon programme was nominally secret, the judgement of international non-proliferation experts at the time was that South Africa was indeed building nuclear weapons.[c] However, the declared timeline shows that South Africa probably did not have enough highly enriched uranium (HEU) to have conducted a nuclear test by September 1979. This claim was supported by the IAEA team analysing enrichment records.[d]

During the 1993 visits, International Atomic Energy Agency (IAEA) inspectors queried South Africa's political leadership on this issue several times and received a scripted answer to the effect: 'At no time did South Africa use information from any nuclear test in its nuclear weapons programme.' This was the gist of the answer given several times almost verbatim from senior government officials such as Waldo Stumpf of the Atomic Energy Corporation (AEC). There was a small amount of elaboration in private: South African officials said that South Africa did not conduct a test.

Israel was also suspected of possibly testing a nuclear weapon in this 1979 event. Stumpf made the observation that Israel was almost certainly using plutonium in its nuclear weapons and South Africa was clearly using HEU, so there was no overlap. Israel's weapon would be a plutonium implosion device and South Africa's was a very different gun-type. This speaks clearly to the careful choice of words to the effect that no information from any test had been used in South Africa's weapons. Stumpf made the additional observation that no physical data to support the event had been found, in his opinion. His advice was to ask the US Government.[e]

The still standing official US position is that the satellite detection was a random event.[f] The USA officially closed the case with an expert report in 1980 and has not re-opened it.[g] However, it is important to remember that this event took place at a time during the US presidency of Jimmy Carter when there was strong political pressure to conclude that this was not a nuclear explosion.

As of the time of writing, the international conclusion is that Israel conducted a nuclear test of some sort on 22 September 1979.[h] Many experts and analysts have provided scientific and anecdotal assessments that a nuclear event did occur. Some, such as hydroacoustic data, are scientific and contradict the US official report.[i] There is also evidence from a court case that South Africa provided Israel with port and logistical facilities to stage the test from a barge in the ocean.[j] Dieter Gerhardt, a South African naval officer convicted in 1983 of spying for the Soviet Union, claimed in 1994 that he had learned through 'unofficial' channels that the Vela incident was the outcome of Operation Phoenix, a joint Israeli–South African nuclear weapon test (possibly a neutron bomb).[k]

[a] Rhodes, R., *The Twilight of the Bombs: Recent Challenges, New Dangers, and the Prospects for a World Without Nuclear Weapons* (Alfred A. Knopf: New York, 2010), p. 164.

[b] US National Security Council, 'Discussion paper: South Atlantic', 7 Jan. 1980.

[c] Pabian, F. V., 'South Africa's nuclear weapon program: lessons for US nonproliferation policy', *Nonproliferation Review*, vol. 3, no. 1 (fall 1995), pp. 1–19

[d] Stumpf, W., Atomic Energy Corporation of South Africa, 'Birth and death of the South African nuclear weapons programme', Presentation at the conference '50 years after Hiroshima', Castiglioncello, Italy, 28 Sep.–2 Oct. 1995, section 4.

[e] Stumpf specifically said 'Maybe Mr Kelley knows!' in a large meeting.

[f] Rhodes (note a), p. 168.

[g] Sublette, C., 'Report on the 1979 Vela incident', Nuclear Weapon Archive, 1 Sep. 2001.

[h] Burr, W. et al., 'A blast from the past', *Foreign Policy*, 22 Sep. 2019.

[i] Reed, T. C. and Stillman, D. B., *The Nuclear Express: A Political History of the Bomb and Its Proliferation* (Zenith Press: Minneapolis, MN, 2009), p. 178. See also Wright, C. M. and De Geer, L.-E., 'The 22 September 1979 Vela incident: The detected double-flash', *Science & Global Security*, vol. 25, vol. 3 (2017), pp. 95–124; and De Geer, L.-E. and Wright, C. M., 'The 22 September 1979 Vela incident: Radionuclide and hydroacoustic evidence for a nuclear explosion', *Science & Global Security*, vol. 26, vol. 1 (2018), pp. 20–54.

[j] Richelson, J. T., *Spying on the Bomb: American Nuclear Intelligence from Nazi Germany to Iran and North Korea* (W. W. Norton & Co.: New York, 2006).

[k] Richelson (note j).

next evening the test party had received an order from the government to stand down immediately and return to base.[38] The site was disassembled overnight and sensitive equipment was returned to Pelindaba. Many pieces of equipment were buried in the rush to evacuate in case there was an on-site inspection by foreigners.

Despite suspicions to the contrary (see box 3.1), at no time did South Africa use information from any nuclear test in its nuclear weapon programme. Moreover, the South Africans stated that they never intended to conduct an atmospheric test at Vastrap, such as on a tower. There was a steel tower over the test hole, but its purpose was to support cables and winches for lowering the test device into the hole. The South Africans did say that they were not sure they could stem (i.e. close up and seal) a nuclear test, and they were concerned that some of the debris could escape.

In 1987 and 1988 there was further activity at the site and a garage-type structure was built over PG-1. This activity by the Armscor programme managers was to reassure the government that Phase 3 of the deterrent—conducting a test—was still possible. It is also the time when the nuclear warheads were finally being manufactured. When IAEA inspectors first visited the site in 1993, they were presented with a cover story that the new building was a garage. A stand for draining engine oil had even placed to hide the top of the underground test shaft.

The test hole was nevertheless discovered by the inspectors. It had been capped by South Africans with a concrete cover, which they photographed as evidence During this process, rodents and birds ran across the wet concrete, leaving a unique pattern that would be modified if the concrete cap were ever clandestinely removed and replaced. This unwittingly created a 'tag' over PG-1 that is similar to the more sophisticated seals used by the IAEA for nuclear material containers.

The IAEA supervised the closure of the two test shafts in 1993. An interesting historical note is that the shafts were located in a nature preserve and the closure was public despite the formerly secret nature of the project. Using local sand dunes would have violated environmental regulations. Therefore, despite the availability of tonnes of sand at the site, sand had to be trucked-in from Uppington, outside the nature preserve, to comply with the rules. The hole was filled-in with sand and some debris (e.g. drums filled with cement and iron scrap).

[38] Reed and Stillman (note 33), p. 176.

The IAEA was briefed on an observable that tied Kentron headquarters and the Vastrap and Pelindaba sites together: a uniquely shaped white truck about the size of a delivery van that was seen at all three sites. It was examined at Kentron Central and was simply a mobile photography laboratory and darkroom.

4. The Pelindaba site

During the 1970s the AEB—more precisely, its Reactor Development Division (RDD)—had plans for a stockpile of nuclear weapons. Experimental activities for the weapon programme began at Pelindaba in the 1970s. It is not clear whether the SADF was an enthusiastic supporter of the programme. The lack of military requirements in programme documentation suggests that it was not very involved. The RDD designed a small gun-type nuclear weapon intended to fit in a glide bomb (see box 2.1 above). It did early testing and development largely in a group of small buildings in the bush just outside the main AEB complex at Pelindaba. The most important of these were Building 5000 and Building 5200.

Uranium enrichment at Pelindaba

In 1970 UCOR was founded and began working on a unique isotope-separation method at the Pelindaba nuclear research complex near Pretoria. This method, called Helikon, used large amounts of hydrogen gas to propel uranium hexafluoride (UF_6) gas through tiny holes in a tube in what is known as a stationary centrifuge.[39] This process separates out the lighter uranium-235 isotope from the naturally predominant isotope uranium-238. Natural uranium consists almost entirely of the isotope uranium-238. Nuclear fuel typically requires the proportion of the fissile isotope uranium-235 to be increased from less than 1 per cent to 3–5 per cent, known as low-enriched uranium (LEU). An enrichment of 20 per cent or more is known as highly enriched uranium (HEU), while weapon-grade uranium must be enriched to approximately 80 per cent uranium-235 or more.

The Helikon process was energy intensive, inefficient and dangerous due to the large amounts of hydrogen. The process was developed indigenously to avoid international controls and was so inefficient that no one else ever considered using it again. A fact that is largely ignored in descriptions of the Helikon process is that a small amount of UF_6 gas was carried through the process in vast quantities of explosive hydrogen carrier gas, creating a notable safety risk. The entire enrichment plant was filled with pipes and filters containing hydrogen. Much of the interior design was focused on hydrogen containment, electrical safety equipment, fresh air venting and emergency ventilation. One of the main features of the Pelindaba enrichment plant, easily seen from public roads, are the seven tall stacks for flaring hydrogen gas in case of an emergency. There are no reports of any significant hydrogen explosions. No other country has developed such a system and, because of its cost and complexity, UCOR never exported enriched uranium produced through the Helikon process.[40]

[39] Stumpf (note 3); and US Central Intelligence Agency, Directorate of Science and Technology, 'South Africa to fund preparatory work for full scale uranium enrichment plant', *Weekly Surveyor*, 11 June 1973, pp. 1–2.

[40] Stumpf (note 3), section 2.

Parts of the Helikon plant—called Valindaba or the Y Plant—became operational in 1975 and by 1978 it had begun to produce HEU.[41] The Helikon process worked well when using high-quality UF_6 feed imported from France.[42] In 1979 the plant began using indigenously produced UF_6 and the process collapsed quickly due to contaminants in the feed material: the contaminants quickly plugged up the millions of tiny holes in the stationary centrifuge.[43] Resolving this problem took over a year. This probably involved the re-fluorinating of the plant using a strong fluorinating compound such as chlorine trifluoride (ClF_3) and renewed quality control over UF_6 production.

This pause in enrichment of uranium was at the time of the Vela incident over the South Atlantic (see box 3.1). The problems at the Y Plant mean that South Africa could not have produced enough HEU to conduct a test by September 1979, contributing to the assessment that another country was responsible for that test.

By 1982 the Y Plant was operating reliably. It continued to produce HEU until 1990, when enrichment was discontinued. The Y Plant was not subject to IAEA safeguards: under its Type-66 safeguards agreement, South Africa was not obliged to declare this plant.[44] Its processes and output remained secret although its sheer size attracted international non-proliferation attention.[45] During this period a considerable backlog of HEU accumulated because production of weapons halted due to safety problems in the nuclear device caused by barrel misalignment (see chapter 5). The inability to produce any more nuclear explosives during the peak of the threat from Cuban troops in Angola, first due to the failure of the enrichment plant and then safety problems in the device, was a major contribution to ending the programme.

The nuclear engineers on the project had hoped to use the considerable backlog of HEU produced by the AEB during this period to build a fast burst reactor for physics studies. Armscor never allowed this, even when device manufacturing paused. It put the material into storage instead. One justification for this refusal that Armscor could have used was that the uranium would have become mildly radioactive if used in a pulsed reactor for a long time. That would have made its subsequent use for weapon manufacturing more difficult. Moreover, such a reactor would have contributed virtually nothing to the nuclear weapon programme.

The Building 5000 complex at Pelindaba

Buildings 5000 and 5200

Building 5000 was designed for criticality testing, which involves bringing together subcritical masses of HEU until they are critical—meaning that they

41 von Baeckmann et al. (note 14).

42 Albright, D., 'South Africa's secret nuclear weapons', Institute for Science and International Security (ISIS) Report, May 1994.

43 Albright(note 42); and Stumpf (note 3), section 2.

44 Type-66 safeguards agreements are based on IAEA, 'The agency's safeguards system', Information Circular INFCIRC/66/Rev.2, 16 Sep. 1968.

45 Burns, J. F., 'South Africa ousts 3 US embassy aides, charging air spying', 13 Apr. 1979, *New York Times*.

can produce a sustained chain reaction. This is common work in the nuclear field, but dangerous. It is normally done remotely because personnel would be exposed to lethal radiation and the possibility of a sudden unexpected event—a criticality accident. Building 5200, at a safe distance, was the control building for the criticality testing in Building 5000.

AEB engineers conducted initial experiments on the criticality of a uranium sphere in Building 5000 in the 1979 time frame. These experiments were not designed to closely mock-up the geometry of the gun-type weapon, but they were similar in mass and geometry. By calculating the critical mass of the uranium sphere and then verifying it through experiments, computer codes could be tested and validated. If the codes confirmed the experiments in Building 5000, then they could be expected to also accurately predict the bomb geometries.

Tests were done in Building 5000 on a 35-kg sphere of uranium enriched to 80 per cent and reflected by 10-centimetre-thick stainless steel neutron reflectors (see figure 4.1). The 'sphere' was a stack of several plates because it would be dangerous from a criticality safety standpoint to manufacture it as a single piece.[46] This was especially true during neutron-moderated operations such as electroplating. Stainless steel was used because it was easier to obtain and machine than the tungsten–copper reflector/tamper used in the real bombs. At the time, in 1978, the capability of the programme to make high-density tungsten–copper had also not been demonstrated (see table 5.1 below) and a facility with hot isostatic press for making tungsten–copper parts had not yet been built (see chapters 5 and 7).

Criticality control was achieved using control rods made of steel with a steel safety block at the bottom. If instruments detected that the criticality was starting to get out of control, the safely block would drop and stop reflecting neutrons. This schematic does not appear to follow safety guidelines and procedures in critical assemblies developed by other countries. The codes were shown to be accurate.

The 1/M experiment: Approach to critical

A $1/M$ experiment is a common activity in nuclear criticality science to determine when criticality will be reached. It is not particularly esoteric, but it is a basic safety step when assembling critical masses by hand or remotely. Simply put, a neutron source is placed next to subcritical masses that are to be assembled to be critical. As the masses are moved together, the neutrons from the source create a chain reaction in the uranium and the subcritical multiplication factor, M, increases. The arrangement is exactly critical when M has reached infinity. Since it is hard to plot M against the distance between the two masses as M extrapolates to infinity, the operator instead plots $1/M$ (i.e. 1 divided by M): the assembly can then be predicted to be critical when $1/M$ approaches zero. This is standard procedure in any criticality measurement.

[46] Horton, R. E., *Out of (South) Africa: Pretoria's Nuclear Weapons Experience*, US Air Force Institute for National Security Studies (INSS) Occasional Paper no. 27 (INSS: USAF Academy, Co., Aug. 1999).

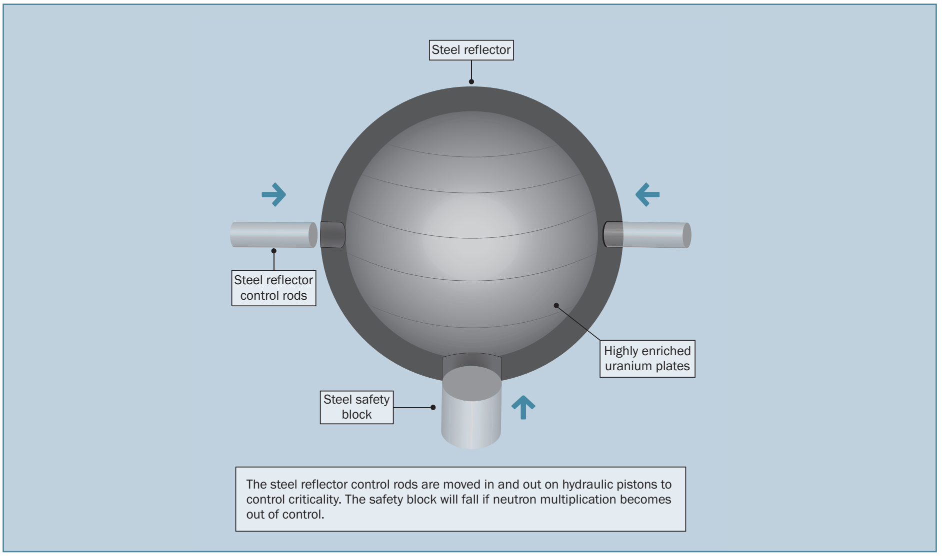


Figure 4.1. The critical assembly in Building 5000

Note: This was not a pulsed reactor and it was not an exact mock-up of the future bombs. It was built to verify nuclear design codes in a simple geometry. Criticality control was achieved by moving reflector plates in and out.

Buildings 5000 and 5200 were designed to carry out this possibly hazardous task safely, with control separated from the experiment. But in 1979 the decision was made to make the $1/M$ measurement on the first nuclear device as a hand assembly in Building 5200. The front end and rear end projectile components were placed horizontally on the tabletop next to a neutron source. With a neutron counter ticking away audibly, an operator pushed the projectile slowly into the front end with a metrestick. A safety block was inserted in the empty space so that the projectile could not be inserted beyond the calculated safe point.

When the experimenter plotted $1/M$ versus insertion of the projectile, it was clear that the device would have gone supercritical and exploded as the computer codes predicted. This validated the codes and ensured that the nuclear device, in this case the second device code-named Melba (see table 5.1 below), was a nuclear explosive that would have exploded as designed. Of course, the experiment was stopped just short of going critical as that would have been suicidal.

An approach to the point at which code is validated is possible, just very ill-advised in this fashion. This is an experiment that a nuclear engineer could have conceived and carried out with aplomb. It would have never passed any management safety review—it was just a case of getting the job done despite the consequences. In addition to safety, there was a lack of attention to security; on at least one occasion when the experiment was conducted, the front and back sections of a device were together in an ordinary building, far from any high-security vaults.

Building 5100

Building 5100 is located at the entrance to this small group of research buildings. At one point there was a small rail gun in the building. The gun could be used to smash masses into each other using high pressure gases or propellants. This would allow scientists to make fine measurements of how materials behave when they are deformed at high impact rates. These equation-of-state (EOS) experiments are common in high-pressure physics and are necessary especially in the design of implosion weapons. There is little use for them in developing a gun-type weapon.

Building 5100 was also the base laboratory for the personnel and equipment for the aborted 1977 nuclear test dry run at Vastrap. Equipment was staged from this site and returned here when the test was abandoned.

At the time of the IAEA visits in 1993, Building 5100 was being used as an armoury for the security guards of the Pelindaba site. Two other small buildings, the size of a garage, were used for preliminary studies of high explosives.

5. Gun-type weapon development and testing capabilities at the Circle facility

Until 1977 the South African nuclear weapon programme remained in the control of the AEB through the RDD at Pelindaba. However, the huge embarrassment caused by the Vastrap test debacle (see chapter 3) and the AEB's politically naive scientists gave the government a reason to change the management. Although the AEB developed and tested device parts for the first small deliverable weapon, change was coming. By 1980 a new nuclear weapon facility, the Circle facility—code-named Castille or Castle—was built at a site near Pelindaba. Instead of the AEB, this was to be managed by Kentron, an armaments development and manufacturing company, on behalf of Armscor. The Circle facility became one of the most important sites in the South African nuclear weapon programme.

The RDD designed the Circle facility in 1979. In addition to capabilities for gun-type weapons, there were also facilities for the future development of an implosion weapon. In particular there were cells for manufacturing and testing high explosives unrelated to gun-type devices (see chapter 7). The RDD transferred the plans to build the small gun-type devices to the Circle facility. The RDD was quickly shut out of the programme and became only the supplier of HEU and not a full partner in the programme.

Armscor approached the programme as a mechanical engineering process—it never changed the nuclear design because it had no competence in nuclear science. The engineers at Circle were largely mechanical and aerospace engineers with no nuclear expertise. For them, the small nuclear device was to be built exactly to a set of instructions provided by the RDD. This meant that they were unwilling to make any changes to the nuclear core. They did make many changes to the non-nuclear parts of the bomb, mostly involving safety and engineering issues, but the nuclear explosive remained untouched. As the management of the programme was transferred to Armscor in the early 1980s, the RDD personnel trained in physics slowly realized that they had become redundant. Most moved to other jobs with the AEB or elsewhere. A few joined Armscor's Circle facility.

The Circle facility is located 8 km east of the AEC site at Pelindaba. The small nuclear programme buildings were disguised by locating them in a hollow in the centre of a large and highly visible motor vehicle testing ground, the Gerotek vehicle testing grounds.[47] The site has multiple roads and speedways for testing military and civilian vehicles. Gerotek is prominent in overhead imagery (see figure 5.1) and would be apparent from adjacent areas because of the activity and noise. The Circle facility was thus hiding in plain sight.

The Circle facility consisted of only two major buildings, both relatively small in size. The main building was a bespoke project to contain almost all of the industrial processes to produce the nuclear explosive devices. It was the production site

[47] Armscor, 'Gerotek'.

for most of the gun-type weapons and a research site for any future implosion weapons. The second significant building was the Circle integration building, which was located on the side of a hill. It is not immediately obvious in satellite imagery that it was actually a series of steps up the side of the hill with activities on several floors, mostly as one large open room.

The main Circle building

The main Circle building had an extensive range of capabilities spread over a ground footprint of approximately 5000 m^2. Most of the facilities were on the ground floor with a small mezzanine for offices and light work such as electronics fabrication.

The gun-type weapon development and testing capabilities located in the main Circle building included uranium metal manufacturing operations; hot isostatic pressing of heavy tungsten–copper tamper pieces and gas centrifuge magnets; machining and assembly of other metals; electronics fabrication; testing cells for gun-type weapon propellant experiments; an assembly bay for final assembly of gun-type weapons; safe areas for handling propellants and pyrotechnics; and offices and common areas.

Uranium metal manufacturing operations

The Circle facility received uranium metal ingots from Pelindaba. The UF_6 from the enrichment plant was reduced to metal before it was sent to Circle. Only one of the two casting furnaces at Circle was used; the other was a back-up.

At the general uranium handling area, only shoe covers and laboratory coats were used for contamination control of uranium radioactivity. Uranium was machined on covered lathes and operators used respirators. Since uranium corrodes quickly in air, metal uranium parts were electroplated with nickel for corrosion protection. Some plating failed and had to be redone.

Hot pressing of tungsten, its alloys and samarium–cobalt magnets

Hot pressing of the tungsten–copper tamper around the HEU core of a gun-type weapon was a critical technology pathway. The main purpose of the heavy tamper was to provide inertia to delay the expansion of the reacting material during the explosion. This gives time for more neutrons to initiate fission of more nuclei, thus increasing the efficiency and yield of the weapon. The tamper also acted to a small extent as a reflector around a bomb—pushing neutrons back into the exploding nuclear mass—allowing it to be manufactured slightly smaller. Materials with a high atomic number such a tungsten are poor reflectors, but they do reflect a few neutrons.

Machinable tungsten–copper powder was hot pressed in a bespoke press made from a gun barrel and gun barrel breach closure. The basket containing the tamper pressing was 241 millimetres in diameter and 254 mm high. The export of a press of this size would have been limited under typical export controls in exporting

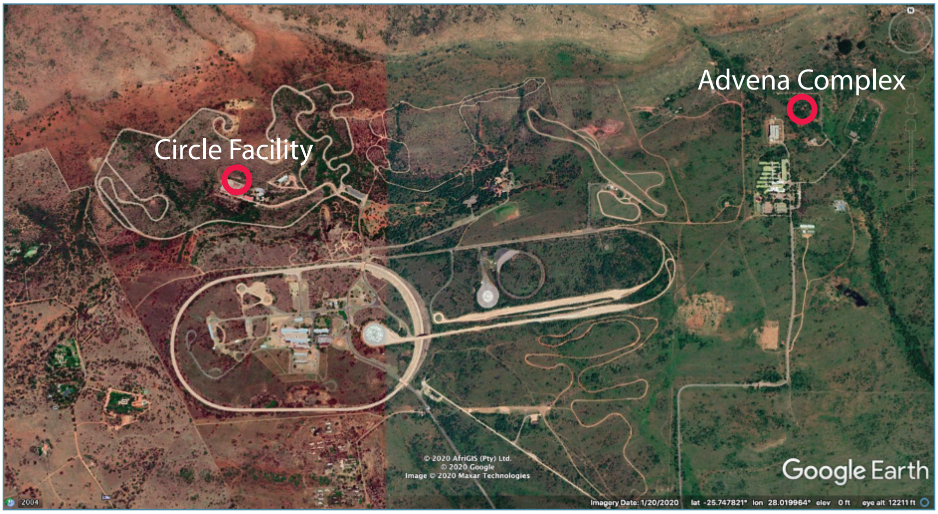


Figure 5.1. The Circle facility hidden inside the Gerotek Vehicle Testing Centre
Note: Advena is located just to the east.

states.[48] However, the bespoke press allowed South Africa to make the tamper in a number of segments (smaller than the export control limit) instead of in a single cylinder or hemisphere. Some of the initial tungsten–copper pieces were declared to have been made under contract, but the IAEA did not visit the contractor site.

The tamper outside the HEU static mass was not adversely affected by being made in segments. Discontinuities in a converging shock wave, as in implosion, would be a greater problem but this is not the case in a gun-assembled weapon's external mass tamper. South Africa's innovation to bypass export control requirements designed to prevent tamper manufacture was to use a tungsten–copper mixture—this was necessary to allow machining after pressing since pure tungsten would have been hard to machine. South Africa gained experience with time in increasing the density of the tamper pieces (see table 5.1 below). In turn this allowed better tamping in later models. Some of the claimed densities were almost the same as pure tungsten. That would indicate much less than 10 per cent copper, which is not typically sold by commercial suppliers today. Varying tamper density is one of the reasons that almost every bomb had a different yield from the others. A tamper less dense than uranium would not reflect shocks back into the uranium as well as one with a density like pure tungsten or uranium. After the end of the programme the hot press was used commercially to produce tungsten–copper electrodes for high voltage switching at another Armscor plant, Pretoria Metal Pressings (PMP). It was discovered later that the press had also been used to produce magnets for gas centrifuges (see below).

[48] The Nuclear Suppliers Group (NSG) publishes guidelines for countries implementing such controls. International Atomic Energy Agency (IAEA), 'Nuclear-related dual-use transfers', Communications Received from Certain Member States Regarding Guidelines for the Export of Nuclear Material, Equipment and Technology, INFCIRC/254/Rev.1/Part 2, July 1992, annex para. 1.5.

Making the tamper from natural or depleted uranium would have been a simpler solution. It would have been much easier to manufacture and would produce a tamper with impedance that matched the density of the exploding core. However, natural uranium is a strong source of stray neutrons. Since the South African nuclear devices did not use an initiator, they depended on a stray neutron to start the chain reaction explosion. If there are too many stray neutrons, such as from a natural uranium tamper, there is a significantly increased probability that a stray neutron will start the chain reaction too early in the assembly. This is called preinitiation and would result in either a failure to explode or a failure to achieve expected yield. By deciding not to use a neutron initiator that would have supplied enough neutrons at precisely the right moment to start the chain reaction, South African scientists chose to rely on a statistical probability that a stray neutron (e.g. from a cosmic ray) would always arrive in time. They estimated that it was acceptable to wait for such a neutron to arrive for 2 milliseconds once the HEU 'bullet' and 'target' had assembled. This meant that there would be a good chance that at least one of the stockpiled bombs might be a dud, making the dependable stockpile smaller.

Steel machining

Good-quality machine tools were used for machining a variety of components such as the gun barrels and associated parts. A five-axis CNC mill purchased for the implosion programme was the highest quality single piece of equipment found at Circle. It would have been used to make complex timing tracks on a spherical surface.

Electronics fabrication

Bespoke electronic components were produced in the electronics shop of the Circle building.

Testing cells

The west end of the building had cells for energetic testing of materials including large quantities of propellants and explosives. (On explosives see chapter 7.) Full-scale mock-ups of gun-type weapon assemblies were conducted in a heavily reinforced cell. The cell was lined with railroad ties in case of massive mechanical failure, which did occur during development. The Circle engineers described an example of the failure of bolts holding the gun barrel to the front end during test assemblies.

These tests used depleted or natural uranium components in place of HEU. South Africa did not consider that natural uranium or depleted uranium were nuclear materials and did not record quantities or apply safeguards to them before it joined the NPT.

Assembly bay

Final assembly of each nuclear explosive device took place in a bay at the far west end of the building. Each device assembly was treated as a new criticality safety event despite the fact that all the parameters were known. Interestingly, the mechanical engineer in charge of the assembly declared that 'It was important to bring the uranium pieces together slowly, rather than quickly, to avoid a criticality accident'. However, the speed of assembly of a known subcritical mass is not the danger—this illustrates the fact that nuclear physics expertise was not transferred from Pelindaba to Armscor and the Circle facility, where operations were carried out by engineers, chemists and metallurgists but not physicists.

Safe areas for energetic materials

The entire west end of the Circle building was designed for work with hazardous materials such as high explosives and propellants. The safety culture and design were good practice in 1990.

Offices and common areas

About 150 people could work in the Circle compound at any time. Most arrived by bus and there was a covered parking area to hide cars and trucks from overhead observation. The site was designed to look like a storage facility, so a lot of vehicles would have been inconsistent.

The South African counterparts indicated that they kept track of observation satellites through satellite tracking services (there were few observation satellites in that era) and tried to minimize outdoor operations during known overflights. An example of caution is that a staff request for an outside volleyball court for exercise was denied.

The integration building at Circle

The integration building was an area for environmental and mechanical testing, development of components, and quality control. It was solely dedicated to the gun-type weapon programme. This was where engineers tested components to see if they would survive broad temperature ranges using ovens and coolers and vibration forces in transport and deployment. There was a small centrifuge for testing accelerometers to see if they functioned properly in sensors for arming and firing of the weapons.

The building had no chemical activities, including tritium operations. It was not designed to handle significant quantities of explosives or propellants but could handle ordinary pyrotechnics such as squib valves, cutters and explosively driven motors. There were lightning arresters, which attests to the presence of pyrotechnic materials.

An interesting miscommunication involving the integration building occurred during the IAEA visits. The author observed that one of the IAEA inspectors, whose mother tongue was French, became quite upset when the hosts explained that electronics for the devices were brought to this building for 'burn-in'. Burn-in is jargon for the process whereby new electronics are turned on and operated for about 100 hours to check that they work and will not suffer infant failure. The inspector virtually accused the guides of lying because he felt it was obvious that no ‘burning’ operations could be safely conducted in such a building. The translation problem was quickly resolved but it illustrates language difficulties in inspections.

Kentron Central

The aerospace company Kentron provided administrative cover for the nuclear weapon programme. Recruitment of personnel was done through Kentron Central headquarters in Verwoerdburg near Pretoria (now renamed Centurion). Recruits could be interviewed at this site far from the seat of the programme. Suitable candidates would receive security clearance and be admitted to the Circle facility.

Kentron is still located in Centurion, renamed as Denel Dynamics and part of a larger government-owned company. It produces aerospace products such as small missiles, unmanned aerial vehicles and, notably, glide bombs. It is worth recalling that the South African nuclear weapons were designed to be used in glide bombs: the IAEA specifically agreed not to investigate delivery systems (see box 1.2) and was unaware of this connection at the time.

Kentron was the business face of the programme for activities such as purchasing. The credit rating of Kentron was used for vendors that would not be able to judge the credit worthiness of the secret programme. Kentron had a circle in its logo in those years, which has sometimes led to modern confusion with the Circle facility 25 km away.

The name Advena/Kentron Circle is used today in open source publications about the former South African nuclear programme. Such an association would have been highly classified at the time of the programme.

Findings for the gun-assembled weapon design

By the time the South African nuclear weapon programme came to end in the late 1980s, it had only managed to build a few nuclear devices. Each had a number and code name (as shown in table 5.1). One was not weaponized and had few safety features. It was reserved for a low-yield nuclear demonstration test of about 4 kilotons. The five weaponized devices in the stockpile all differed in their uranium enrichments and in other ways. The HEU components for a seventh device were produced but never completed. Five of the final seven devices were built (or were being finished) in 1988 and 1989.[49] This can be regarded as a major failure on the part of Armscor: too little and too late. The government decision to wind down the programme had already begun in 1985.[50]

This highlights a common misstatement about the speed of the programme. Stumpf, for example, notes that South Africa produced about one device per year during the 1980s.[51] This is statistically true—on average—but misleading. In fact,

[49] Gould (note 29), p. 106.
[50] Stumpf (note 3), section 5.
[51] Stumpf (note 3), section 4.3.

Table 5.1. Versions and designations of weapons

Note the regular use of biblical names for the devices.

Designation	Device name	HEU enrichment (% U-235)	Density of tungsten–copper reflector/ tamper (g/cm^3)[a]	Completion date	Note
Video (later Melba)		81.5	?	Nov. 1979	Test device for explosion; no weaponization or safety features
Hobo (later Cabot)		?	?	Dec. 1982	First weaponized device
306	Feniks	90	19.25	Front: June 1986 Rear: June 1988	Initially a cold testing device; later a weapon
501	Maria	90	16.25	Front: Aug. 1987 Rear: June 1988	Weapon
502	Ikabod	90	16.46	Front: Jan. 1988 Rear: July 1988	Weapon
503	Skulla?	90	15.88	Front: Nov. 1988 Rear: Mar. 1989	Weapon made by disassembling pieces of Cabot
504	Abraham	90	19.37	Front: Mar. 1989 Rear: Mar. 1989	Weapon
Set 7	Menora	90	?	. .	HEU machined and plated—not completed

? = unknown data or uncertain designation; . . = not available; HEU = highly enriched uranium.

[a] Tungsten–copper tamper density ranged from 16.7 g/cm^3 to 19.3 g/cm^3 for later models.

Source: Author notes; and Gould, C., 'The nuclear weapons history project', ed. K. Allan, *Paper Wars: Access to Information in South Africa* (Wits University Press: Johannesburg, 2009), pp. 88–121, p. 106.

it produced no device for about six years and then produced four devices between June 1988 and March 1989 with another in the pipeline (see figure 5.2). The average number built from 1982 to 1989 is a meaningless statistic.

The Armscor Circle project was organized in an orderly way, as would be expected of a military aerospace contractor such as Kentron. The IAEA was

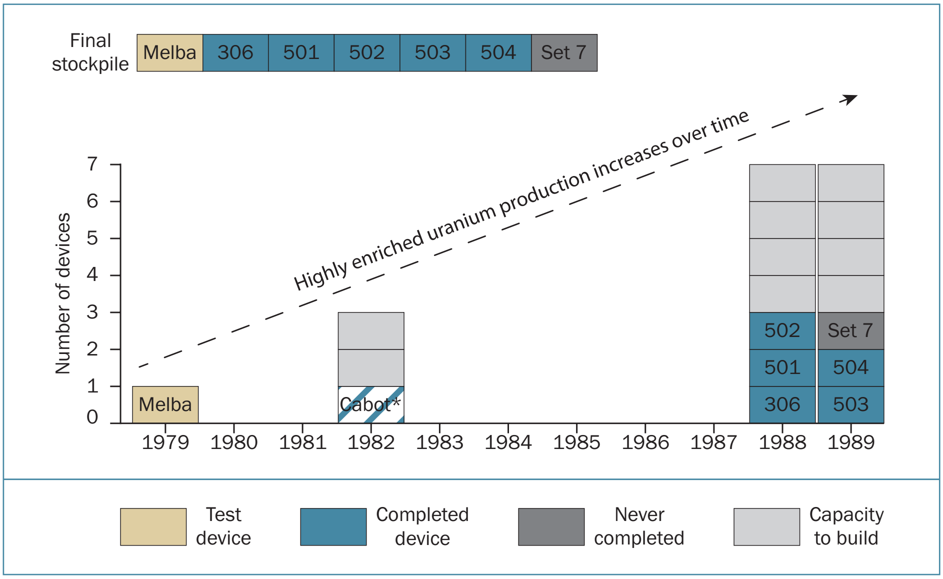


Figure 5.2. Year of device builds

Note: All of the weaponizable devices were built in 1988 and 1989 except for Cabot, which was disassembled to build device 306—the final approved design—in 1989.

able to examine build records for each device.[52] South Africa had retained one box of documents for each device for the IAEA even after the devices themselves and most other documents had been destroyed. This was to assist the IAEA in preparing a completeness report to the effect that the devices had been built, that verifiable amounts of HEU were involved and that the devices had been destroyed. The South Africans and the author worked to ensure that critical nuclear weapon design information was closely held. Other information such as dates and timelines were shared with other members of the IAEA team.

There were detailed records for each device that documented each part in the device and where and when it was manufactured. They could be broken down into three types: (*a*) engineering change proposals (permanent); (*b*) deviation certificates for a planned deviation; and (*c*) concessions for a one-time unplanned deviation from a specification.

Of interest were the large numbers of deviation and concession reports. These reports document approval of parts that did not meet at least one specification but were certified on a case-by-case basis for exceptional use. This is typical good practice in industry when a missed specification on an expensive part can be judged to be acceptable.

[52] International Atomic Energy Agency, GOV/2684 (note 16); Kerr (note 14); and von Baeckmann et al. (note 14).

Table 5.2. Estimated yield of various configurations of South African nuclear weapons

These are South African estimates, not the author's.

Uranium enrichment (% U-235)	Density of tungsten–copper reflector/tamper (g/cm^3)[a]	Yield, as estimated by South Africa (kilotons TNT equivalent)
80	. .	4
90	16.7	14
90	18	19

. = not available.

[a] Density of 16.7 g/cm^3 is the industrial specification for hot pressings of tungsten–copper composite in the ratio by weight of 90 : 10. Density greater than 19 g/cm^3 was probably pure tungsten.

Source: Author notes; and Midwest Tungsten Service, 'Copper tungsten alloy', [n.d.].

Military requirements

The South African nuclear weapon programme was a product of the civilian AEC. For that reason, civilians were more influential in setting programme requirements than the military. Throughout the programme the SADF seemed reluctant to embrace the programme. One source reports that the first time the SADF even became aware of the nuclear weapon programme was in 1974 when it was asked to provide some security for the Vastrap nuclear test site.[53] Throughout the 1970s and 1980s South Africa was involved in a war against rebels, revolutionaries, and Cuban and Angolan troops. Most of the fighting was in open territory against relatively small or dispersed targets for which a nuclear weapon would not be very effective. Given that the programme was effectively limited to six deployable nuclear devices, it is questionable how and if they ever would be used.

This explains why the yield of the weapons was not a top requirement. This is an unusual observation for military analysts from most nuclear-armed countries: they would expect a set of weapons with a reproducible yield for anticipated missions. Instead, the South African weapons had various yields depending on which device was to be employed—each South African weapon was unique with a yield that depended on the enrichment of the nuclear material and the density of the outer tungsten–copper tamper (see table 5.2).

The dimensions of the planned weapon were set at 1.5 metres long and 30 cm in diameter. The nuclear device was estimated to weigh about 430 kg. It would use a much thinner reflector than the initial PNE and South Africa expected it to give a yield of about 3–4 kt. The small version would be used in a nuclear demonstration test. The gun barrel used about 350 grams of conventional gunpowder to propel the 90-mm-diameter projectile. The projectile train included a nose of tungsten alloy at the front and one at the back of the uranium to complete the tamping and reflecting at assembly.

The front end consisted of the HEU and the tungsten–copper tamper pieces. They were all held together in a bolted steel shell. The core design had no bolts,

[53] Gould, C., 'The nuclear weapons history project', ed. K. Allan, *Paper Wars: Access to Information in South Africa* (Wits University Press: Johannesburg, 2009), pp. 88–121, p. 115.

pins or step joints. This meant that the assembly of approximately 13 pieces inside a steel shell was hard to align. This is important: when the projectile arrives after being shot down the barrel, the hole in the sphere needs to be straight and aligned. To deal with this problem, the front end core was assembled by hand, possibly in the bolted shell. The assembly was then taken to the integration building at the Circle facility and shaken on a vibrating table for many minutes. An alignment fixture was inserted in the centre hole so that the pieces vibrated into the straightest possible alignment. Then the bolts were re-tightened in the steel shell.

Mechanical arming was set at 2–4 seconds. The SADF required that the device work throughout a temperature range of –40 to +70 degrees Celsius. This provided engineering challenges for machining tolerances and things like lubricants that might freeze or boil away. These temperatures extremes could occur on a hot runway or at 15 000 metres in the air.

The weaponized device was predicted to have a yield of roughly 14–19 kt (see table 5.2).

Safety and security as paramount military requirements

A huge amount of attention was given to safety and security. The government wanted strong assurance that the devices would not explode until they were armed and at their targets. It also wanted high assurance that the devices could not be used without authority from the highest level of government. The gun-type weapons were ideal in both respects.

It is easy to engineer that the front and back ends can be built separately and stored separately. As long as they are separated, there is no chance that they can assemble and explode accidentally or be misused without collusion of at least two people.

Security was provided by keeping the front and back halves stored in completely separate vaults with different access controls on each.[54] When a device was being worked-on, only one front or one back could be removed from a vault at one time. Two people were required to open any vault door together and two different people were required to open the other door. Two senior civilians from the AEC and two authorized by the government were required to open two doors at once and assemble a working device.[55]

There were three sets of vaults in the programme. One commonly shown in open-source photographs was in the Circle building.[56] A second one was at the Witbank Coal Mine and was only used temporarily from 1979 to 1982 for the storage of the device code-named Video until Circle was completed. A little-known fact is that there was a third set of vaults in the Advena integration building that was probably never used.

[54] von Baeckmann et al. (note 14).

[55] von Baeckmann et al. (note 14).

[56] Richelson, J. (ed.), *US Intelligence and the South African Bomb*, National Security Archive Electronic Briefing Book no. 181 (National Security Archive: Washington, DC, 13 Mar. 2006).

Table 5.3. Designations and purpose of the non-nuclear devices of the South African nuclear weapon programme

Designation	Date	Notes
101	Feb. 1982	Model device assembly; 2 tests using various amounts of propellant
101		Used in 460 kg bomb test
102	Feb. 1982	Overload test of barrel and mechanical parts
102 reused	Jan. 1983	Test of stop ring in the catcher
201		Non-nuclear components testing
202	1982	Dummy payload simulator
203	1982	Dummy payload simulator including self-destruct mechanism
204	1984	Advanced development model
301	1984	Test in cell
302		
303		
304		Cold
305		
306		Initially cold then highly enriched uranium
307		Test in cell
420–24	1986	Mechanical tests at high end of temperature range

When the devices were ready to be used for explosive purposes, they could be assembled together quickly, within hours, and taken to a military site for insertion into a military delivery system.

Nuclear explosive safety is also completely assured when the device is disassembled in two sections. If the projectile cannot be inserted into the static mass, there can be no explosion. Coupled with electrical safety on the propellant in the gun, there are few dangers.

Nevertheless, the engineers worried that the projectile could accidentally propel down the barrel if the device was tilted incorrectly or the propellant somehow ignited before intended detonation—this was a major roadblock in the programme.[57] The solution was to intentionally misalign the portion of the barrel containing the projectile to the barrel leading into the front end. Only when the device received a final arming signal would the barrel move into alignment so that the projectile could be fired into the front end mass. This simple mechanical task required an electric motor and microswitches. The alignment would occur in the final 4 seconds before the device was intended to go off, normally an air burst. There was also a ground contact mode, salvage fusing, whereby the device could detonate as it hit the ground if the air burst sensors failed.

An additional safety issue was the case where a bomb was dropped in error or jettisoned due to aircraft problems. In such a case there would be no electrical arming signal. But when the bomb hit the ground, the impact might cause the projectile to slide into the front end. The misaligned barrel was supposed to

[57] For a detailed description see Albright with Stricker (note 6), p. 110.

prevent this. Unfortunately for the South Africans, they conducted a drop test of a dummy device and the misaligned barrel was not sufficient to keep the projectile from entering the mass. This would have resulted in a nuclear explosion in an event where a bomb hit the ground even when it was not fully armed. On friendly territory this would be a disaster.

This explains the gap in completion of devices: no devices were produced between 1982 and 1986 and no rear ends were produced again until 1988 (see table 5.1).[58] The fault was probably discovered in a test of dummy bomb 102, 202 or 203 (see table 5.3). During this period there was considerable re-engineering of the rear end section and its safety interlocks. The misalignment was modified to be more effective. Blow-out holes were added to the back of the barrel. If the propellant was ignited by accident, then the force of the propellant gases would be dissipated through the holes. The holes would only have been closed in the final arming sequence.

During the period between 1982 and 1988 when no weapons were manufactured, enough HEU for several devices must have accumulated. It is not clear how well this stockpile was protected.

The moving barrel provided one other problem. If it were moved at the wrong time it would marginally affect the moment of inertia of a re-entry vehicle. This probably was a minor problem even in the ballistic missile warhead because the movement was largely on the centre axis and did not shift mass to the sides.

These examples highlight the importance given to safety and security by the programme engineers and managers. They also highlight that, despite a rapidly deteriorating military campaign in South West Africa and Angola, the nuclear programme was not such a high priority—if it had been, then more money and manpower would have been diverted to the programme.

Permissive action links

The host engineers made frequent reference to the term permissive action link (PAL) and associated it with their safety and security philosophy. The PAL is the sequence of events that must take place in order to take an inert weapon into the active mode until it explodes. The first thing in the PAL chain is an authorization message from the governmental authority to begin the process. This is followed by a series of mechanical and electrical steps including a series of arming/de-arming switches, mechanical safing devices and signals from a fusing system that take the bomb out of a safe mode and tell it to explode at the correct time. The South Africans were firm in the use of the term PAL—which is US jargon—and obviously had spent a great deal of time researching US procedures.[59]

Initiator in the gun-type bomb

Most nuclear explosives contain an initiator. This is a small device that emits a burst of neutrons at a precise time to start the chain reaction in a supercritical

[58] Gould (note 53), p. 115 and table 4.1.

[59] E.g. US Senate, Committee on Appropriations, *Energy and Water Development Appropriations Fiscal Year 1988*, part 2 (US Government Printing Office: Washington, DC, 1988), p. 1683.

Table 5.4. Code names and designations used in the programme

Code name or designation	Meaning
A Star	Boosted bomb programme
Aralia	Tungsten
Candy	Uranium–titanium alloy
Castille or Castle	Circle facility
Gardenia	Possible demonstration nuclear test of Melba
Limestone	Beryllium
Modulus	Advanced gun-type design for demonstration
Mulberry[a]	Uranium–niobium alloy
Nuance	Implosion development programme
RXD	Depleted uranium
RXV	Highly enriched uranium
View	Advena Central Laboratories

[a] Mulberry is an internationally recognized US code name for a uranium–niobium alloy developed for weapons. This is another indication of how South Africa followed US design work. Williams, R. O., 'Stability of the body-centered cubic gamma phase in the uranium–zirconium–niobium system', *Journal of Nuclear Materials*, vol. 82, no. 1 (June 1979), pp. 184–92.

mass and 'light' the nuclear explosion. An initiator is an absolute necessity in an implosion bomb. In a gun-type bomb it is almost, but not absolutely, essential.

There are many ways to build an initiator. One is to use a reaction between two substances that emit a burst of neutrons when mixed. Such an initiator could, for example, use the radioactive element polonium when mixed with beryllium to emit a burst of neutrons. This so-called crush initiator was used in early US and Soviet devices. Polonium is a deadly material, even in tiny quantities, and needs to be produced in a nuclear reactor.[60] South Africa's SAFARI-1 reactor could be used to make polonium in sufficient quantities, but it was under IAEA safeguards and policymakers were reluctant to use it for such purposes—producing polonium for use in a military device would have been a violation of South Africa's Type-66 safeguards agreement with the IAEA, which prohibits military use of a safeguarded facility.[61] In addition, polonium is radioactive and decays quickly, and so requires nearly annual replacement. This is undesirable in a military system that always needs to be at the ready. Finally, the timing of the neutron burst to within microseconds is important and would require significant development and testing.

The other way to make a neutron initiator is to build a small nuclear accelerator, the size of a soft drink can. This is not particularly difficult but there are serious problems with getting the device to function at exactly the right time—within microseconds. South Africa did not feel capable of addressing the problem, so it simply left out the initiator.[62]

[60] On the widely reported poisoning of Alexander Litvinenko using polonium see e.g. Owen, R. (chair), *The Litvinenko Inquiry: Report into the Death of Alexander Litvinenko* (House of Commons: London, Jan. 2016.

[61] IAEA, INFCIRC/66/Rev.2 (note 44).

[62] Stumpf (note 3), section 8(i).

The solution was to wait for a cosmic ray to enter the supercritical mass and start the chain reaction naturally, or to hope that a stray neutron from spontaneous fission in the uranium itself would come at the right time. Statistically this is a pretty safe bet. A cosmic ray or stray neutron will almost certainly arrive within a millisecond or so, which is not too long in a mechanically assembled device. Scientists who work with pulsed critical assemblies can describe their nervousness when the stray neutron takes tenths of a second to arrive.

The South African engineers simply put a ratchet on the rear end projectile. When the projectile was seated in final position after firing, the ratchet stopped it bouncing back out before the explosion could start. As with much of the South African programme, this solution to a physics problem was a fairly crude mechanical solution.

Criticality safety in the front end

The front end of the South African device contained the bulk of its HEU mass. If it were submerged in water, for example in the case of an accident, then the water would act to moderate the speed of a naturally passing neutron, thereby increasing its ability to fission a uranium nucleus and possibly leading to the HEU going critical. This would not cause a nuclear explosion, but it could create a serious radiation accident. There was even some concern that a human hand inserted into the centre hole would act as a neutron moderator and might cause an accident under some circumstances.

The solution to this problem was to line the central void of the front end static mass with a cadmium sleeve. Cadmium is a copious absorber of neutrons and would prevent a criticality accident. Cadmium is also a soft metal, easily extruded. The sleeve served to be crushed by the projectile when it entered the front end and slightly soften the shock of the flying mass hitting the end of the barrel.

Smyth report

The South African engineers had obviously been studying the vast amount of literature published about the US nuclear weapon programme. For example, there were many places they could read about PALs and triaminotrinitrobenzene (TATB) explosives being developed at the USA's Los Alamos and Livermore National Laboratories.

The chief engineer kept referring to a 'secret' book that the South Africans used in much of their planning. After some hesitation he retrieved the book from the safe and it was the famous Smyth report.[63] This unclassified report on the USA's Manhattan project was made public in August 1945, but the South African programme had marked the book 'Secret'. It is an interesting road map of the right way to organize a bomb programme, but it is hardly secret.

The programme used many code words for classified activities and materials (see table 5.4). These words could be used between knowledgeable colleagues in telephone conversations, for example.

[63] Smyth, H. D., *Atomic Energy for Military Purposes* (Maple Press: York, PA, Aug. 1945).

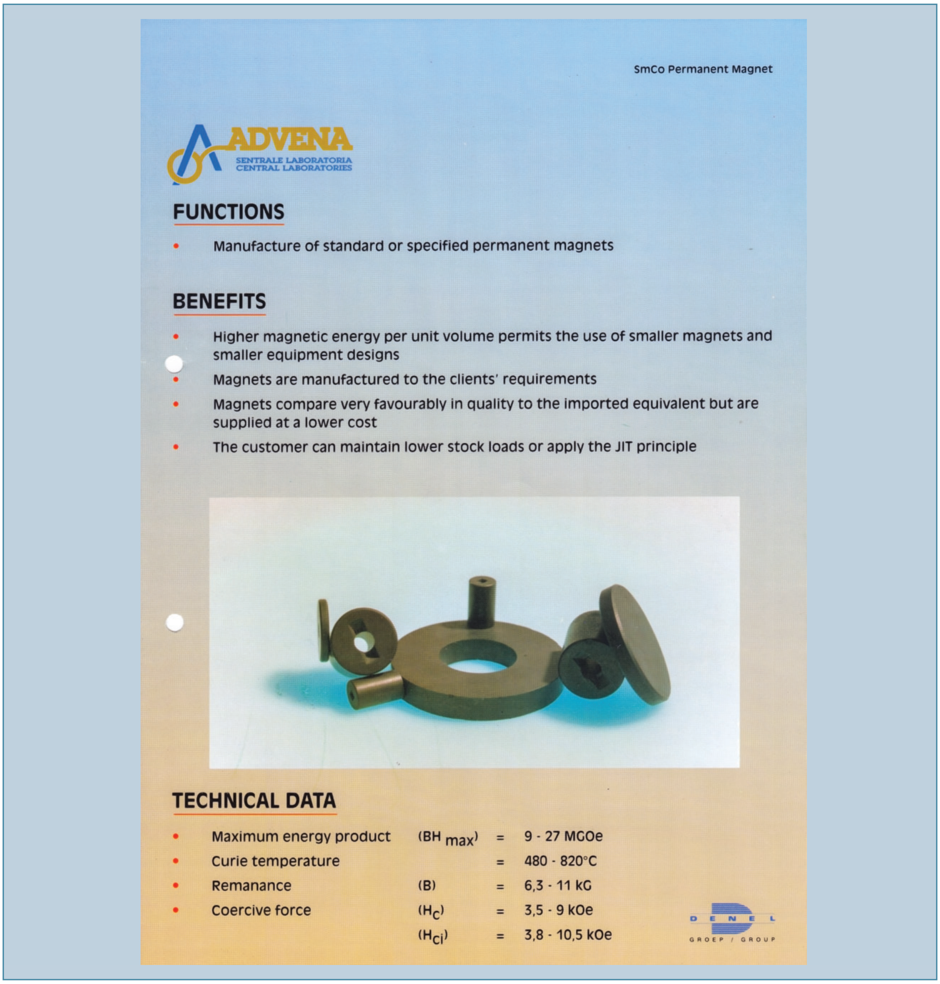


Figure 5.3. Advena sales brochure for samarium–cobalt magnets, 1993

Note: Samarium–cobalt ring magnets made at Circle and later at Advena were probably for the gas centrifuge programme.

Interchangeable warheads for bombs or missiles

A simple question for the South African engineers was how they planned to allot the few warheads they had to the delivery systems. It was clear that the devices were originally designed to be used in an aircraft-carried glide bomb that could reach out beyond the borders of the country. This was because Soviet SAMs employed by the Cuban forces were wreaking havoc on the SADF aircraft.

The other delivery system under development was an intermediate-range ballistic missile (IRBM) based on the Israeli Jericho II.

There were only five weaponized warheads, plus one being completed and one non-weaponized nuclear test device (see table 5.1). How could these be allocated in any strategic way? The answer was simply that the nuclear explosive systems were interchangeable between the bombs and the re-entry vehicles. The idea of using a crude gun-type nuclear explosive in a ballistic missile system seemed surprising at first. Then the engineers demonstrated that the size and weight of the advanced gun-type explosive was similar to, or smaller than, many implosion nuclear devices. Under these circumstances the five (planned six) warheads could have been allocated to either military system.

During the course of inspection discussions in 1993, the lead South African host was asked what the range of the Jericho II was. He turned to a colleague and said, ‘How far is it to Luanda?’; ‘Something like 2200 kilometres’ his colleague replied. The answer to the question about the Jericho’s range was then given as ‘2200 kilometres’. This was a clear sign that the nuclear warhead was being considered as a more strategic deterrent.[64] This would be consistent with the effort that was put into producing tritium for a boosted gun-type bomb with an estimated yield of 100 kt.

Hot pressing of magnets for gas centrifuge bearings.

It is often overlooked that Circle produced magnets for the gas centrifuge programme to enrich uranium. Circle’s mission was not entirely dedicated to weapons although the Circle engineers had little idea what the product was for. The magnets were about 70 mm in outside diameter and 90 mm high (see figure 5.3). They were made of samarium–cobalt and were expected to be magnetized to 18 megagauss. Magnets in this size range magnetized to greater than 1 megagauss-oersted were on the trigger list of UN Security Council items prohibited for shipment to Iraq in the 1990s.[65]

The manufacturing of samarium–cobalt magnets continued after the weapon programme ended. It was one of Advena’s leading products based on a sales brochure of the time (see figure 5.3). Advena was advertising magnets with a maximum energy product of 9–27 megagauss-oersted, well in excess of the UN export limit. These magnets generally match or exceed limits by export authorities.[66]

The IAEA approached the South African visits as a task to verify what was declared by South Africa. South Africa declared that it had a large uranium-enrichment programme based on the Helikon stationary centrifuge process. South Africa did not declare a gas centrifuge enrichment programme. In the IAEA summary, gas centrifuges were not even a footnote. In fact, Somchem was building carbon fibre centrifuge rotors based on modern European technology associated with the British–Dutch–German company Urenco. Centrifuges were being tested at Pelindaba but were ignored by the IAEA because they were not contributing to the declared uranium stockpile.

[64] See also Stumpf (note 3); and Gould, C., ‘The nuclear weapons history project’, ed. K. Allan, *Paper Wars: Access to Information in South Africa* (Wits University Press: Johannesburg, 2009), pp. 88–121, pp. 97, 115.

[65] US Department of Energy, Nuclear Transfer and Supply Policy Division, *Handbook for Notification of Exports to Iraq: Annex 3* (Sandia National Laboratories: Albuquerque, NM, Apr. 1998), p. 3.2, para. 22.2(a).

[66] US Nuclear Regulatory Commission (NRC), ‘Illustrative list of gas centrifuge enrichment plant components under NRC’s export licensing authority’, NCR Regulations, Part 110, Appendix B, 29 Aug. 2017.

Unfortunately, magnet-production technology from Circle was sold to a private company on the break-up of the weapon programme.[67] That technology was transferred back to the AEC at Pelindaba in the 1990s.[68] Personnel and equipment from that project were marketed to the A. Q. Khan proliferation network at the same time as that network was using former Pelindaba staff to build bespoke UF_6 handling equipment to be used in Libya's clandestine nuclear programme.[69] In about 1999 Pelindaba and the AEC formed a commercial company with Tridelta Magnets of Germany. The consortium purchased a samarium–cobalt magnet plant owned by Rareco in western Cape province near Somchem.[70] Tridelta was previously associated with providing centrifuge magnets to the Khan proliferation network.[71] The company, Tridelta Pelindaba (Pty) Ltd, briefly had 100 employees but was liquidated in 2000.[72] There is no record of the disposition of the assets of the company but this is in the period when Khan was supporting UF_6 production development for Libya. In 2004, when the IAEA became interested in the Khan network and the South African involvement in Libya, the remnants of the centrifuge programme were gone and the few documents that remained in Vienna were largely lost or destroyed.

[67] Author interview, 2004.

[68] Author interview, 2004.

[69] Reed and Stillman (note 33), p. 183.

[70] Moneyweb, 'Tridelta—long term buy for recovery'.

[71] Bürgerinitiative Umweltschutz Hamm, 'URENCO-Gate in NRW!' [Urenco-gate in North Rhine-Westphalia], THTR Rundbrief no. 111, Mar. 2007.

[72] 'Court approves liquidation of Tridelta Pelindaba project', IOL, 9 Feb. 2000.

6. Lithium isotope separation, the tritium programme and molecular laser isotope separation at Pelindaba

In the 1970s the RDD had had bigger plans at the Pelindaba site for a more modern and efficient nuclear weapon. One of the goals of the programme was to produce plutonium and tritium for boosted and implosion weapons. This project was known as the Extended Reactor Development Division (ERDD). It gained momentum during the period when the Helikon enrichment programme was foundering and tapered off when HEU supply became more reliable.

Both plutonium and tritium need to be produced in a nuclear reactor, ideally one designed for such a purpose. Generally, they have been produced around the world in military reactors under a military programme. Plutonium is produced in the reactor by the capture of neutrons on uranium-238 atoms—either uranium in the reactor fuel itself or dedicated targets. It is then removed by an expensive, difficult and dangerous chemical separation called reprocessing.

The South Africans had a futuristic concept that they would try to boost the yield of the gun-assembled bomb using tritium. The rough South African estimate was that a boosted gun-type bomb would have a yield of about 100 kt.[73] Tritium can boost the yield of a simple fission device by a factor of two to five. It is produced in a reactor by the irradiation of lithium by neutrons. The RDD seriously considered using lithium isotope separation to make tritium for boosting of fission devices and even for thermonuclear, fusion bombs. In 1980 it built a tritium-handling building at Pelindaba for research on boosted weapons and laid out plans for a tritium- and plutonium-producing reactor at Goriqua, on the south coast of Cape province. There was no military requirement for a 100-kt bomb in the battle against troops in open countryside in the Angolan War. This was one of the best arguments against continuing the boosted bomb programme. It is conceivable that military planners might have considered 100 kt to be useful against a large target such as a city, but they did not get that far in their planning.

Lithium isotope separation

The separation of lithium isotopes was never a leading goal of the South African programme. It is, however, an indication of what was being thought about for the future and what technologies were under consideration. Lithium isotope separation was mostly oriented towards boosting. Lithium-6 is a desirable target material in a nuclear reactor for producing tritium for boosting. However, in the end South Africa concluded that natural lithium was 'good enough'. Lithium was

[73] South Africa declared quantities such as yield, mass of uranium, size of boosting capsules etc. These are South African estimates and are neither confirmed nor assessed.

also considered for a lithium deuteride–tritide (LiDT) boost 'pill'. Lithium-6 for thermonuclear weapons was a distant future prospect.

As early as the mid-1970s work was authorized on producing lithium-6 using well-known chemical separation technology based on a mercury–lithium amalgam exchange process. Experiments were done to measure single-stage separation factors. These experiments are known as reflux and did not produce lithium-6 because it was continually recycled. The goal of this process was to produce 5 kg per year of 95 per cent enriched lithium-6 from natural lithium (which has nominally 7.5 per cent lithium-6).

Design was completed in 1985 for large columns for lithium isotope separation using this process. The columns—up to the height of a 10-storey building—were to be built at Goriqua, about 75 km west of the town of George, Cape province, and would be ready by 1994. The land was purchased and a number of bore holes were drilled in preparation for building large industrial structures, but ultimately an engineering office trailer was the only building on the site. Large-diameter piping to manufacture the columns was purchased but never assembled. There was no further development and the project was abandoned. The size of the planned reactor was not given by the programme personnel and there had been no plan for a reprocessing facility. Site studies continued after the military programme was terminated in case the site was later needed for a civilian power reactor.

Little work was done on alloying lithium with aluminium to make reactor targets for tritium production. Unalloyed lithium metal is pyrophoric—liable to ignite spontaneously—so this is not trivial research. Expensive equipment (e.g. pumps to pump heavy mercury and mercury amalgam) came from Switzerland. As of 1993 this equipment was all for sale.

Serious work on lithium isotope separation ended in 1985 at the same time as authority to produce boosted bombs was withdrawn (see below). Some work continued on lithium separation using atomic vapour laser isotope separation (AVLIS). This was cutting-edge technology in 1980. Apparently, an AVLIS system was built and operated successfully but it was not inspected by the IAEA. South Africa reported good separation factors at high vapour pressure, which boded well for high throughput.

As of 1993 the AVLIS system was still operational. By 1993 Pelindaba had shifted interest from purifying lithium-6 for weapons to purifying lithium-7 for reactor acidity control. Lithium hydroxide can be used for pH control in reactor cooling water. Lithium-6 is an undesirable impurity for reactor coolant because it absorbs neutrons needed for power production and it produces unwanted tritium in the cooling water. There is no indication that this goal was ever reached.

The tritium programme at Pelindaba

South African physicists considered enhancing the yield of the gun-type bomb using tritium as a boosting gas. This project for a boosted bomb was called A Star (see table 5.4). Tritium (hydrogen-3 or T) is a rare isotope of hydrogen. There are two natural isotopes, protium (hydrogen-1 or H) and deuterium (hydrogen-2 or D), while tritium is man-made. The A Star programme never even broke ground on a tritium-production reactor so the only way to get tritium was to purchase it. Israel was able to supply the tritium: 19.92 grams were declared to have been purchased in 1977 from Israel in four steel containers.[74] Other sources give the final total as 30 grams although this was not officially declared.[75] No tritium is known to have been produced at any time in South Africa.

The tritium project was housed in a nondescript building in the Pelindaba complex near the SAFARI-1 reactor. The boosting project was not successful or likely to succeed and never made significant progress. The peak of activity was in 1982–83 and the work was terminated in 1985.

Even the concept of boosting a gun-type weapon is a marginal activity. Gun-type nuclear weapons do not easily get hot enough to cause tritium to fuse with deuterium, so boosting may not even occur. Physicists associated with the programme pursued engineering goals for the boosting. They planned for about 5 grams of tritium in a boosted gun-type bomb.[76] They recognized that the gas would need to be in a small capsule inside the uranium gun assembly either in the form of tritium gas or a compound such as lithium tritide (LiT). They estimated that the capsule would be about 1 cm in diameter, made of steel and possibly reinforced by a layer of stronger material applied by chemical vapour deposition. The chosen strengthening was nickel carbonyl, which would be used to create a strong surface layer. They calculated (correctly) that this would necessitate a pressure of up to 1000 atmospheres. This would involve compressing an isotope of hydrogen that is highly radiotoxic to extremely high pressures. Hydrogen is a notoriously difficult gas to contain. It leaks through many solid materials, valves and gaskets. This was a daunting mechanical engineering task. The physicists also understood that tritium is constantly decaying into helium-3, which both increases the pressure in the capsule with time and counteracts the positive contributions of tritium by absorbing neutrons.

They considered storing the tritium as a compound, perhaps uranium tritide. However, they had done enough research to realize that uranium tritide would be unstable and difficult to make and store. Alternatives were LiT or LiDT. The people interviewed were mainly material scientists and not familiar with the physics of boosting. Analogues of LiT were made in the programme using lithium hydride (LiH) and lithium deuteride (LiD). These studies never overcame serious practical problems because the boosting programme ended before serious development.

The tritium facility that was built at Pelindaba had some notable features. There were six columns, each 7 metres tall and 15 cm in diameter, for purifying the tritium by thermal diffusion along a tungsten hot wire. Four of the columns were used to strip out undesirable isotopes and two were used to enrich the tritium

[74] von Wielligh, N. and von Weilligh-Steyn, L., *The Bomb: South Africa's Nuclear Weapons Program* (Litera Publications: Hatfield, 2016), p. 296.

[75] McGreal, C., 'Apartheid-era minister carried "nuclear trigger" in hand luggage to South Africa', *The Guardian*, 3 June 2010.

[76] The quantities of tritium required for boosting, the size of the boost capsules and pressures to contain are a composite of South African interviews and represent their goals, not an independent assessment.

product. This is standard procedure to isotopically separate tritium from any deuterium or ordinary hydrogen (protium) that has contaminated the tritium. The tritium facility was professionally designed for hydrogen handling and used commercially available high-vacuum valves and important details such as gold gaskets in joints, impermeable to hydrogen.

The South African team recognized that the decay product, helium-3, is a valuable material in its own right. It can be irradiated in a reactor to make tritium again and it has special value in certain neutron-detecting devices. In 1993 they declared that they had about 10 grams of helium-3 in storage and that they had no plans to irradiate it in the SAFARI-1 reactor. Helium-3 is a copious absorber of neutrons and would have a severe impact in the operations of SAFARI-1. These numbers are consistent with South Africa's stockpile declaration and the radioactive decay of tritium.

Eventually the tritium was used for commercial purposes beginning in August 1987. The AEC at Pelindaba manufactured products such as small self-lighting pellets that could be used in applications such as electricity-free safety lights. The operators of the facility exhibited samples of small lights about 1 cm in diameter. The commercial project took only 9 months from conception to producing viable samples. It is not clear that there was ever a commercial sales operation.

One source erroneously claims that the Circle integration building was a tritium-processing building. It was thoroughly inspected and had completely different functions; no tritium work was declared or likely even possible.[77]

Molecular laser isotope separation of uranium

In 1993 there was a significant effort to separate isotopes of uranium using molecular laser isotope separation (MLIS) in former Helikon buildings at Valindaba. Scientists had made a significant effort to determine spectroscopic properties of gaseous UF_6 cooled by expansion through a nozzle. This is the approach that was used by a number of western countries before being abandoned in favour of AVLIS.[78] The South African scientists gave some of the IAEA visitors a tour of the MLIS facilities—the progress they had made was very impressive.[79] The spectroscopy was up to the standard of the day and laser development was ahead of some of the abandoned programmes in developed countries.

Unfortunately, MLIS was a technology of the future and of no importance to resolving the past weapons programme, so it was not investigated further. South Africa was also concerned about protecting industrial secrets from competition—

[77] Pabian, F. V., 'The South African denuclearization exemplar: Insights for nonproliferation', Presentation LA-UR-12-00413, Los Alamos National Laboratory, [n.d.].

[78] US House of Representatives, Committee on Appropriations, Subcommittee on Energy and Water Development, *Energy and Water Development Appropriations for 1985*, part 6 (US Government Printing Office: Washington, DC, 1984), pp. 849–50.

[79] Kemp, D. M., Bredell, P. J., Ponelis, A. A. and Ronander, E., 'Uranium enrichment technologies in South Africa', eds Y. Fujii, , K. Takeuchi and T. Ishida, *Proceedings of the International Symposium on Isotope Separation and Chemical Exchange Uranium Enrichment : October 29–November 1, 1990, Tokyo, Japan* (Tokyo Institute of Technology, Research Laboratory for Nuclear Reactors: Tokyo, 1992), pp. 115–22.

particularly with regard to a German member of the IAEA team. The programme was not ultimately successful and was dismantled in the late 1990s by the post-apartheid government.

7. Implosion weapon development and testing at Circle and Advena

The basis of the South African nuclear weapon programme was the gun-type weapon described above. Throughout the programme there was consideration that an implosion nuclear weapon would be much more efficient in use of nuclear materials (see box 7.1). The engineers guessed that two or three times as many implosion weapons might be made from the same amount of uranium. Implosion weapons can be quite small, although the South African gun-type weapon with a yield of about 15 kt in a small package and reasonable weight could already be carried on an IRBM.

The interest in an implosion weapon was important enough that the Circle facility, designed by the RDD and built in 1980, had a section devoted to high explosive research for such a weapon. This included massive cells for high explosive formulation, pressing, machining, preparation of samples and a 2.5 kg capacity testing chamber.

In 1985 the government decided to limit the nuclear weapon programme to the seven gun-type devices.[80] Clearly the programme was losing support. But in the same year Armscor managed to get funding for a new programme: the Advena programme to develop uranium implosion devices. The Advena laboratories were largely built between 1986 and 1988 for this new mission while small-scale testing of high explosives began at Circle—in obvious contradiction to the government decision to limit the number of devices. The argument for the Advena project was that, since implosion devices use HEU much more efficiently than gun-type devices, the latter could be melted down to make 15 or more implosion devices using uranium that had already been paid for. Continuing the inefficient Helikon process to produce HEU was far too expensive.

This programmatic ploy by Armscor is familiar to military historians. When the main mission is accomplished it is necessary to generate a new mission or find another job. Advena was the new programme. The new facilities were modern and bright, almost like a university campus, unlike the dark and crowded Circle facility.

Advena approached the AEC for people and support. Little was forthcoming. In the years since the RDD had been excluded from the programme, the staff had found other careers and were reluctant to re-join the secretive bomb programme. In any case it was too late.

[80] Stumpf (note 3), section 4.

Implosion weapon development and testing capabilities in the main Circle building

The South African nuclear weapon programme recognized that modern high explosives were necessary for an implosion bomb. The engineers had the capability to formulate critical explosives themselves at Circle. They experimented at Circle with cast explosives such as mixtures of trinitrotoluene (TNT) and hexogen explosive (RDX). The results were not satisfactory. The better materials they produced were largely powders and they had the capability to press the powders into small experimental pieces such as plane wave generators. Pressed plastic bonded powders (PBX) blended with binding powders such as wax or Teflon are the basis of modern high-quality explosives such as nuclear weapon lenses.[81]

Efforts to produce and study high explosives began at Circle, led to frequent testing at a military artillery testing range near Potchefstroom (see chapter 8) and were to end at Advena Central Laboratories. The main Circle building had facilities for formulation and manufacturing of high explosives and for testing and diagnostics. There were also cleverly designed ceiling panels in manufacturing cells that would blow out into a hidden roof plenum in the event of an accident in the cell.

High-explosive formulation and manufacturing

High explosives were produced from raw materials via remote-controlled wet chemistry processes in the west end of the building.

There was some remote-controlled casting of explosives in manufacturing cells. Circle had a furnace for melting and casting TNT and also tried TNT–RDX mixtures (Composition B) with poor results. The Circle building had limited capabilities to produce explosive powders. A number of cells were dedicated to remote processing of materials.

Powders could be cold pressed with binders to form plastic-bonded explosives such as octyl and hexogen. The list of binder materials tested at Circle was conventional: wax, Viton, Kel-F and acrylic.

In one manufacturing cell there was a cold isostatic press capable of pressing 8–10 kg of PBX. This is equivalent to about 5 litres of high explosive. Pressing is a dangerous operation. An accident here would have definitely caused the blow-out rupture discs to fail and could have caused collateral damage in the high-explosive section.

Testing of high explosives

Small-scale testing of high-explosive samples could be carried out in the Circle building. Tests of detonators and small samples could be done in sealed cells. There were two dedicated firing cells. Experiments involving up to 2.5 kg were carried out in an explosive cell. Contained experiments could be done in a steel tank with up to 100 grams of explosive.

[81] On types of explosive see Klapötke, T. M., *Chemistry of High-energy Materials*, 3rd edn (de Gruyter: Berlin, 2015).

Box 7.1. Implosion weapons

Implosion nuclear weapons work by compressing a subcritical geometry into a much smaller shape and higher density. The smaller object compressed several times above room density will become supercritical and, if done properly, it will produce a nuclear explosion. This was the technology used in the United States' second wartime bomb at Nagasaki. The fissile material can be either highly enriched uranium (HEU) or plutonium. South Africa only had HEU for the entire period of its weapons programme. Production of plutonium was an abstract distant goal.

The subcritical fissile mass must be compressed by a charge of conventional high explosives. The implosion is normally designed to compress the HEU into a much smaller sphere that will be supercritical because of its much-reduced size and higher density. The smooth compressing of the high explosives is the technically challenging part of implosion technology. Many tests of material properties and simulations at small scale are required. Advanced hydrodynamic computer codes that are difficult to obtain and run are necessary. In the 1980s most US weapons analysts would have believed that a country with South Africa's limited technological skills would have needed to have a full-yield nuclear test to be confident that it had a working implosion device.

There were many different kinds of high-explosive tests. Some were designed to measure properties of different explosive formulations. These included dimple tests, sensitivity tests and gap tests. For example, a dimple test is a cheap way to measure the energy of a piece of high explosive by measuring the dimple it makes when it explodes against a standard steel plate. Gap tests measure the sensitivity of an explosive via the gap from a detonator and other sensitivity tests measure such things as safety when explosives are dragged on a rough surface or dropped.

Streak cameras can be used to accurately measure simultaneity of multiple detonators. This was a major effort even for only six detonators, the maximum that South Africa could fire at the same time. Plane wave generators give the engineer an idea of how shock waves transit from a detonator through a block of explosive and come out on the other side. South Africa used diagnostics such as contact pins, optics, streak cameras, framing cameras and Manganin gauges.[82] The Circle engineer in charge of such work estimated that they did about 1000 such tests between 1985 and 1988. Many of the tests were for the purpose of developing diagnostics more than developing a device. Repeatable reliable diagnostics are critical to measuring performance and progress.

Experiments generate surprises. After many experiments involving only bare explosives in the 100-gram tank, the engineers put a piece of acrylic glass (a lightweight transparent plastic) on an explosive block to make optical measurements on a grid. The soft plastic turned into a potent missile when the explosive detonated and made a hole in the steel wall of the testing tank. The engineer carefully pointed out the welded patch on the tank as a clear example of the learning curve for dealing with new and deadly materials.

Design for concealment

Buildings similar to Circle that are used for development of high explosives usually have earthen berms around them: a recognized signature for satellite

[82] Bosson, S., 'Ramrods shepherd hydrodynamic tests', *Science & Technology Review*, Sep. 2007, pp. 4–11.

imagery analysts. Circle reduced this signature by having integral cells that had walls typically 75 cm thick facing corridors and another thick outer wall.

It is common practice to have one wall in a manufacturing cell that is weak and blows out when there is an accident or overpressure. However, blow-out walls might also be observed by satellite or other overhead observation. Circle avoided this by having blow-out discs in the ceilings. These discs were 2–3 metres in diameter and would blow out into the attic of the building in case of an accident. Naturally, these blow-out discs were not used in test cells where the experiment is at the gram scale because they are designed to blow-out only in an accident. If they were used in test cells, they would have to be replaced after every test and would cause cumulative damage to the attic. Larger tests were done in containment tanks or outdoors. The cells for processes such as pressing were designed for emergency venting of one accident only. Hence, these blow-out discs were a clear discriminator of which cells were used for manufacturing and not testing. The attic acted as a large plenum to absorb the shock and gases generated in an accident.[83] It also prevented external observers from seeing anything other than a typical storage building roof.

There was a small storage magazine for explosives just east of the main building. It was designed to have thick walls and did not have the earthen berms typical of a high-explosive building.

Advena Central Laboratories

The new Advena complex was designed in 1986 and initially operational in 1988. It is located about 2.5 km east of the Circle facility (see figure 5.1). It has its own entrance road and is not hidden in the Gerotek vehicle testing range.[84] The mission for the new site was the development of an implosion-type nuclear weapon. The South African implosion weapons would need energetic high explosives to compress HEU into a supercritical mass to create an explosion. Advena was built with all the facilities needed to develop such a weapon, conduct some experiments and manufacture a small stockpile.

Advena was completely dedicated to an implosion programme using high explosives. Some management functions were also moved from Circle to the more cheerful environment of Advena. The new Advena complex was managed by Kentron Central using the same oversight and cover story as Circle. Although in 1993 Advena was under the same management as Circle, virtually all actual weapons work, including programme close-out, remained at Circle. As noted above, open literature in 2020 casually applies the term Advena to Circle using terms like 'Advena Kentron Circle' but this is a result of the old programme being bundled into one site by historians.[85] In 1993 the missions and names were separate.

[83] von Wielligh and von Weilligh-Steyn (note 74), p. 9.
[84] Armscor (note 47).
[85] Reed and Stillman (note 33), p. 181.

Some of the modern tools and instruments installed at Advena were used by Circle. However, Circle remained the focus of the manufacturing programme of the seven gun-type devices. It was also the facility dedicated to producing warheads for ballistic missiles, both gun-type and implosion.

Advena is 3 km west of the large PMP plant, a major manufacturer of armaments and munitions. Both were managed for Armscor but there was no known cooperation during the nuclear programme.

The main Advena buildings

A large portion of the new complex consisted of many small laboratories and offices in modern attractive surroundings. There were many pieces of laboratory equipment of the quality that might be expected in a first-class university such as spectrometers and an electron microscope.

There was a modern three-axis computer-controlled coordinate measuring machine, the type used in the best industrial quality-control laboratories of the time. Notable in this room was the discovery in 1993 of gauging blocks related to the uranium gun-type weapons: polished steel parts of the exact finished dimensions of the uranium pieces were found on a shelf. Parts like these are used to calibrate the measuring machine and 'teach' it the dimensions of a perfect part. The real uranium part is then measured, and deviations are noted. It was obvious to the inspector what these parts were, but the manager in charge of the laboratory said that they had been there when he arrived, and he did not know what they were for. This is an indication that the missions of Circle and Advena had some brief overlap. It also suggests that destruction of classified materials other than HEU was haphazard.

The non-nuclear parts of the actual destroyed weapons were stored in the main warehouse in the office complex in 1993. The tungsten–copper tamper segments were stored on pallets next to cleaning supplies in a room that was open to anyone who worked there. Gun barrel fragments, with ends roughly cut off, were stored there, as well as many other non-nuclear parts. This was a clear sign that complete dismantlement and destruction of weapon components had focused on the HEU parts. The IAEA arranged for these non-nuclear components to be destroyed over the next few years.

The high-explosive development complex

A key part of the new Advena site was a group of six bunkers and a control building in its north-east corner. These were dedicated to high-explosive operations. They had earthen berms typical of high-explosive operations and were readily distinguishable as a small research and development complex.

South Africa disclosed all the bunker functions to the IAEA.

Bunker 1. The plan for this bunker was to buy and install remote explosive machining capability, probably with a two-axis CNC mill.

Bunker 2. This was scheduled to become a machining bunker. In 1993 it was in use producing detonator cord.

Bunker 3. This important bunker was destined to have an isostatic press for making weapon parts from high-explosive powder. This would be a key component in any implosion programme. Significantly, the size and characteristics of such a press had not been decided before the building was built. This bunker was in use in 1993 making cone pack charges for fracturing rock in the mining industry.

Bunker 4. This bunker was reserved for cutting operations for high explosives. Cutting can be dangerous due to friction.

Bunker 5. This bunker was also planned to be used for machining and quality-measurement operations.

Bunker 6. This bunker was to be used to assemble a finished implosion device. The bunker had been licensed to handle less than 200 kg of high explosive. This is slightly less than the expected mass of the conceptual South African complete high-explosive sphere, which was estimated at about 255 kg.

In addition, the building in the middle was a control building for remote operations in any of the bunkers.

The high-explosive testing cell

The high-explosive testing cell was a concrete room with thick walls designed to contain an explosive experiment with up to 10 kg of high explosive. There was a control room where the experimenters could control FXR systems, streak cameras and high-speed cameras. The South African counterpart told an IAEA inspector that the FXR system 'could see through 600–1000 grams of uranium metal'. This is roughly equivalent to a ball of uranium 5 cm in diameter, which is not very interesting in weapon work, especially if the device does not use an internal initiator. Nor is this related to a uranium shell in a weapon. This FXR system would have only been interesting to capture a shadow of the exterior of a ball being compressed, possibly for code development. The walls were lined with old wooden railroad ties to protect the concrete from shrapnel damage in tests. This cell had been used before 1993.

The Advena integration building

The Advena integration building (as distinguished from the Circle integration building) was a long, drive-through building plainly capable of holding a transporter erector launcher (TEL) for a missile system. South Africa clearly stated that this was to enable development testing of mating a warhead with a missile, but this was not a production site.

On the east side of the building were testing machines and equipment such as a spin machine capable of spinning a re-entry vehicle to measure moment of inertia and to balance it. There was a testing machine for flexural moments suitable for stress testing and more ordinary equipment such as lathes and milling machines. In this area there were two vaults for the separate storage of front end and rear end gun-type weapons. This lent credence to the idea that some missiles might carry a gun-type nuclear warhead.

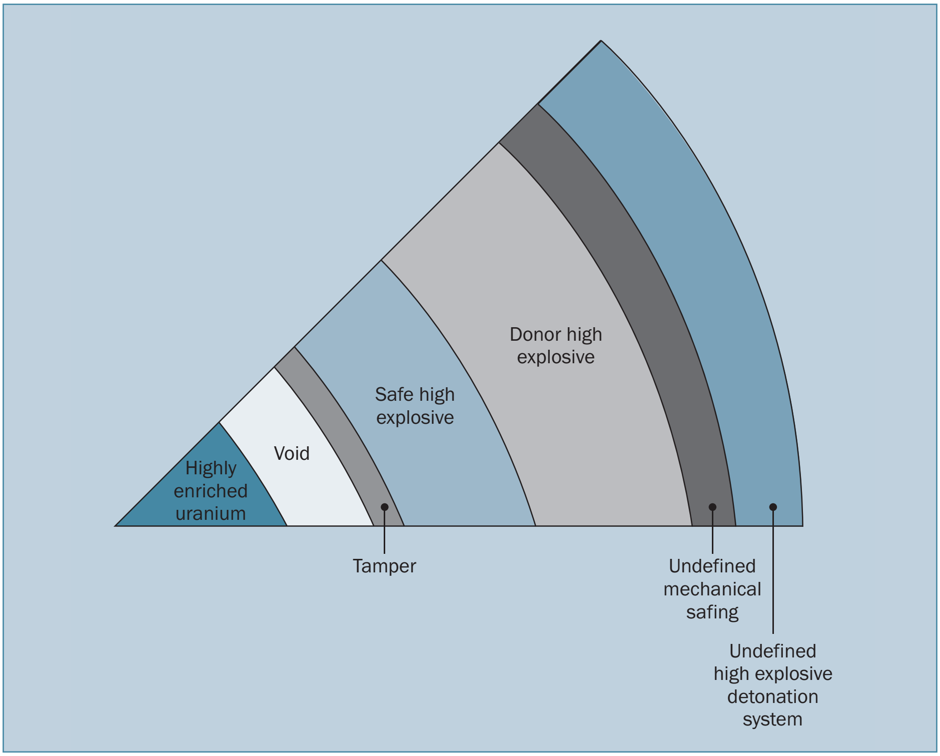


Figure 7.1. South African suggestion for layered components of an implosion nuclear device

Note: This is a South African suggestion not evaluated or confirmed by the author; not to any scale.

The integration building was only licensed to handle 2 kg of high explosives even if canned and contained. If implosion weapons were developed, there would need to have been a re-assessment or a new building.

Smaller buildings and areas

Smaller areas included a burn pit to dispose of high-explosive scrap and a sewage plant. Programme documents were still being burned in a metal cage at the burn pit on 24 March 1993, the day that President de Klerk briefed the parliament that the programme was ending.[86]

Findings for the implosion weapon programme

General specifications for a future implosion weapon

The future weapon would have to be of a size and weight to fit on the Jericho II missile. The general dimensions were an outside diameter of 500 mm with a high-explosive mass of about 255 kg. The core of the device would be made of HEU,

[86] de Klerk (note 13).

about 25 kg.[87] It is also possible that the first estimate of core size was based on the IAEA concept of a significant quantity (SQ). The SQ is often confused by non-specialists in the weapons field as the mass of material needed to produce a bomb: it is not. The SQ is actually an accounting value used by the IAEA to recognize when a material accountancy deviation is significant.[88]

Plutonium would not be an option for many years into the future. The scientists were not comfortable with the concept of a crush-type internal initiator. The plan was to use an external initiator. External initiators consist of a small deuterium–tritium electrostatic accelerator that fires as the nuclear core is compressed to super criticality. This injects thousands of high-energy neutrons into the super-critical assembly to start the explosive chain reaction.

This led to the concept of a solid ball of uranium metal, suspended in a void (see figure 7.1). Several means of suspending the ball were considered. The ball needed to be precisely centred and survive large forces during missile flight and re-entry. Several layering systems of high explosive were under consideration including classical 'Trinity' lenses and more modern lighting systems. The world's first implosion device, Trinity, had a heavy system of lenses igniting a main charge.[89] This system was rapidly improved by better systems that greatly reduced the weight and diameter of the bomb. Lighting systems weigh less and allow a smaller diameter.

Firing set for detonators

The firing set in a nuclear bomb must send simultaneous high-voltage signals to multiple detonators for a perfectly timed implosion. The voltage and current must be high enough to ignite multiple detonators. This makes the design of firing sets with many channels difficult.

An industry leader for firing sets is the US company Reynolds Industries.[90] South Africa had a two-channel Reynolds firing set. It was re-engineered to make an indigenous six-channel firing set, which was used for a demonstration test at Potchefstroom in 1990 (see chapter 8).

Having developed a six-channel firing set, South Africa considered weaponizing a 12-point system. It even had a conceptual 32-point system, which created a pattern—recognizable as the pentagons and hexagons on the surface of a soccer ball—that appears throughout open literature on nuclear weapons. There would be two detonators at each detonation point for reliability.

Among the safety features was a plan to have a destruct charge using the device's detonators. The engineers working on implosion weapons believed that they could fire two separate detonators and cause destruction without nuclear

[87] South Africa declared quantities such as yield, mass of uranium, size of boosting capsules etc. These are South African estimates and are neither confirmed nor assessed.

[88] For a history and explanation of the SQ concept see Goddard, B., Solodov, A. and Fedchenko, V., 'IAEA "significant quantity" values: Time for a closer look?', *Nonproliferation Review*, vol. 23, nos 5–6 (2016), pp. 677–89.

[89] See e.g. Coster-Mullen, J., *Atom Bombs: The Top Secret Inside Story of Little Boy and Fat Man* (John Coster-Mullen: Waukesha, WI, 2014).

[90] Reynolds Industries, 'The history of Reynolds Industries, Incorporated'.

yield. There are many times when such a zero-yield destruction is desirable—for example, if a missile goes off course or to avoid a device falling into enemy hands. There was also a conceptual idea of having an inert material in the core of the bomb that would have to be removed for compression to take place.

The project engineer for the explosive system was young and bright. He observed that uranium metallurgy was a minor problem given the RDD's years of experience, but the simultaneous ignition of many points on the surface of a high explosive sphere was the greatest problem. When asked how he planned to solve the problem, he answered 'with diagnostics'.

The programme gained some momentum in 1985. It started at Circle with many experiments on plane wave generators made in the Circle explosives machine shop. Early experiments started with cast TNT and moved on to mixtures of TNT and RDX. The programme management followed US developments in nuclear weapons, especially safety. The US national laboratories were pressing hard for funding to use a new explosive, TATB, in nuclear weapons. These discussions were widely publicized in official documents, for example unclassified testimony to the US Congress for funding.[91]

TATB explosive

Triaminotrinitrobenzene is a safe explosive that was being introduced into US nuclear weapons in the 1980s. It is extremely insensitive to shock.[92] If, for example, a high-velocity bullet is fired into a mass of TATB, it will not explode. A mass of TATB can survive in a fuel fire, such as in an aeroplane crash, without exploding. These are desirable safety properties. South Africa was concerned about safety and security in its weapons and wanted to adopt TATB in its implosion system. It had not solved the difficult problems of getting the TATB to detonate reliably. It was also designing systems incorporating both TATB and ordinary high explosive such as octyl for greater energy release. Such an approach negates the advantages of TATB alone because the octyl does not have the safety advantages. Octyl is likely to explode when hit by a high-speed bullet and can detonate in a fuel fire. Using TATB and octyl together in an implosion system is essentially a waste of TATB's safety advantages.

The USA was also interested in using TATB for extra safety in plutonium bombs since plutonium is toxic and its dispersal in an accident greatly adds to the damage. Uranium is not nearly as toxic as plutonium. Dispersing it in an accident is not a particularly serious problem. South African engineers had not thought this through.

South Africa was also considering using octyl or TNT or both in detonators for TATB. This is also not a good idea from a safety point of view. The South African scientists synthesized TATB powder in the manufacturing cells in the Circle building. They never succeeded in pressing TATB in PBX.

[91] E.g. US Senate (note 59), p. 1116.

[92] US Government Accountability Office (GAO), *Nuclear Weapons: Additional Actions Could Help Improve Management of Activities Involving Explosive Materials*, GAO-19-449 (GAO: Washington, DC, June 2019).

South Africa's approaches to simultaneous lighting of a surface were all based on timing methods.[93] Producing this complicated shape on the surface of a sphere is a challenging machining job. They had four variations on this theme. One scheme, which involved filling tubes with explosives, was a failure because they could not extrude explosive down a long thin pipe. Other schemes were tried in flat plate geometry with some success. Purchase of a five-axis CNC lathe was expressly approved to develop the scheme for a sphere, but it was never tested.

Neutron generators for an implosion device

South Africa was able to build gun-type weapons without a neutron initiator. This is impossible in an implosion weapon. When the implosion programme was re-invigorated, initiator development began. Since Advena did not have the technical staff to develop this piece of nuclear equipment, the work was contracted to the RDD at Pelindaba. This was due in part to the reluctance of Pelindaba RDD staff to join the secretive weapon programme after being shut out in 1981.

One staff member performed a literature search and began developing a large neutron generator. It was modelled on a rather large experimental device built at Iona College at New Rochelle, New York, in the USA.[94] This research-sized device was definitely not weaponizable: it was the size of kitchen stove with vacuum pumps attached. It was a strange choice for a weapon programme, but at least it was a first effort in a new technology. The AEC provided tritiated discs for use in a glass tube filled with about 10^{-3} millibar of deuterium gas.

The programmatic goal was for a neutron generator that produced about 10^6 neutrons per pulse with a half width of about 10 microseconds. Work continued until 1990. The high-voltage firing circuits produced a considerable amount of electronic noise. It was not clear whether neutron detectors were simply measuring electronic noise from firing capacitor banks or actual neutrons. A workaround was developed to wrap the neutron tube with indium foil and measure neutron activation after multiple pulses. This showed the work was crude and just getting started—while it gave confidence that some neutrons were produced, there was no temporal information about the width, timing or output of the pulse.

According to patents, the researcher for this project had shifted interest to gamma ray backscatter by 1994. It was never a viable candidate for a weapon.

Summary of the implosion programme

Work on implosion weapons was always a low-priority programme running in the background. Yet the RDD managed to incorporate some expensive high-explosive capabilities into the design of Circle before it was turned over to Armscor. Circle personnel gave little attention to implosion until 1985, when the gun-type

[93] Albright, D. et al., 'ISIS analysis of IAEA Iran safeguards report, part II: Iran's work and foreign assistance on a multipoint initiation system for a nuclear weapon', Institute for Science and International Security (ISIS), 13 Nov. 2011.

[94] Braddock, J. V. et al., 'Ion acceleration pulsed neutron generator', US Patent no. 3 173 013, 9 Mar. 1965.

manufacturing programme was struggling and a new mission was required. A lot of money was poured into building and equipping Advena to develop implosion.[95]

This is another case where it is unclear if the SADF was enthusiastically supporting the nuclear weapon programme. Armscor had incentives to continue the programme: funding and prestige. But there is little to show that the SADF was encouraging the project. Instead, it seemed to have been driven by the financial interests of Armscor and Kentron.

[95] Englebrecht, L., 'Book review: How SA built six atom bombs', defenceWeb, 4 Jan. 2010.

8. Other sites of interest

The IAEA visit teams inspected other South African sites that were known and could contribute to past or future nuclear weapons programmes (see figure 8.1).

Naschem

Naschem is a large ammunition plant located 20 km north-north-east of Potchefstroom, Transvaal.[96] There was no declared connection between Naschem and the nuclear weapon programme. The South African authorities agreed to a visit because the facilities and equipment in the testing area at Naschem could be used in a new nuclear weapon programme.

The most relevant of the capacities at Naschem was a small hydrodynamic testing facility built around 1983. The site could handle 8 kg of explosives immediately adjacent to the facility. It was equipped with FXR systems that could provide dual-axis views of an explosive event involving interactions between a metal penetrator and armour. Getting two views of a simulated implosion of a nuclear weapon could help designers validate computer codes. This facility also had two high-speed cameras that would be useful in a high-explosives programme. There was a streak camera plug-in with a 10-microsecond streak. The framing camera was capable of 5×10^5 frames per second. The speed of the framing camera would have been subject to export controls.

It is possible that Naschem supplied some of the raw explosives that were processed further at Circle. This is not a strategic connection. Some plane wave generators were built here but not for the nuclear programme. Naschem experimented with shaped charges (see chapter 2) but only with liners made of aluminium, copper or iron, never tungsten or uranium. Naschem was reportedly interested in depleted uranium armour-penetrating munitions but there is no evidence that it built or tested any.

Alkantpan

The uranium armour-penetrating munitions discovered at Somchem were tested at a military testing ground near the town of Alkantpan, northern Cape province, operated by Armscor. There may have been as few as 10–30 tests in total: the number was imprecise. It was necessary for the IAEA to visit the site even if it was simply a matter of form because any use of nuclear materials is a nuclear safeguards issue.

The visit in August 1993 revealed no activities of interest to the nuclear weapon programme. The site was mostly dedicated to artillery testing. There was an area for the static testing of hollow charges with a uranium liner. There was also an estimate that 'a few hundred' armour-penetrating projectiles had been

[96] Rheinmetall Defence (note 30).

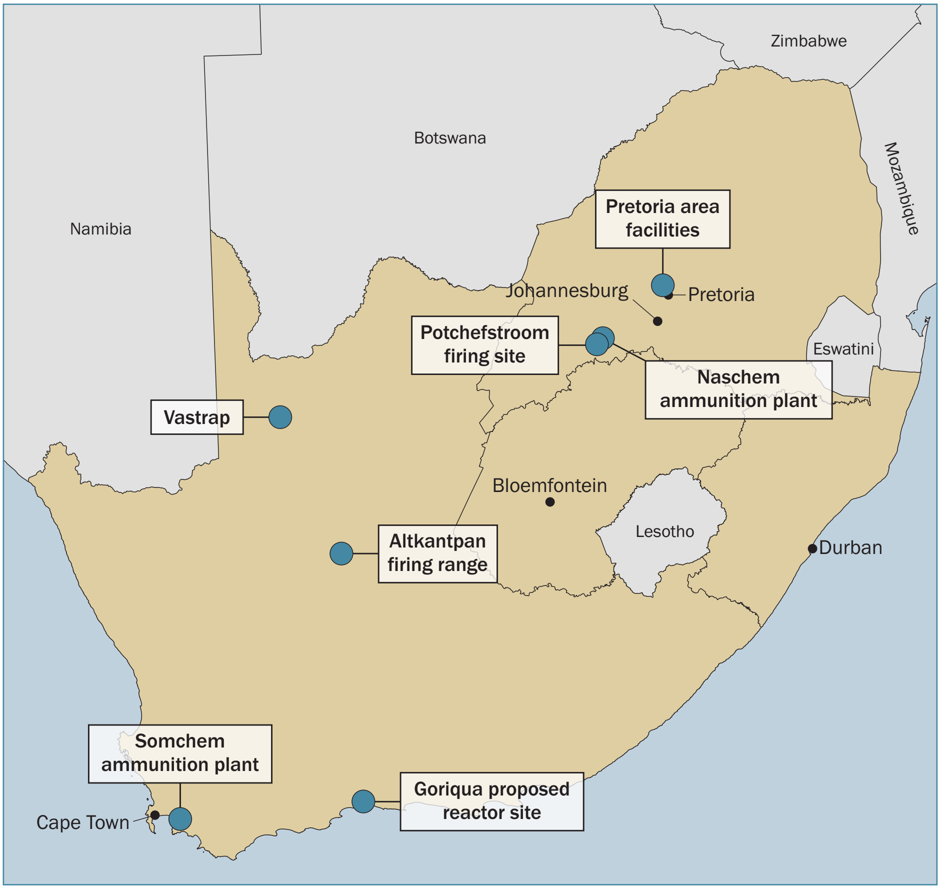


Figure 8.1. Map of the main sites of the programme

Source: Wikimedia Commons, Map of South Africa with provincial borders 1910–76, Htonl.

tested. Some armour plates with holes were found and sampled for uranium contamination (results unknown). The Alkantpan site used high-speed framing cameras (10 000 frames per second nominal or 40 000 frames per second in quarter-frame mode) and streak cameras, but it had no FXR systems of its own. FXR systems from Somchem were brought to the site for the shaped charge tests.

The firing sites were typical of outdoor test ranges. There were small earthen berms to protect equipment. Cameras were protected by earthen berms. The experimenters used mirrors to see around the protection to the device being tested. This is standard practice. There were shards of broken glass scattered about. There was no sign whatsoever of nuclear weapon development, but the expertise and equipment seen here would be a good baseline for such a programme.

Potchefstroom

One of the few unknown facilities discovered by the IAEA in the 1993 visits was a small testing bunker within a military artillery site near Potchefstroom, Transvaal.

Circle established a small testing facility here in 1985 (at 26.6570° S, 27.0334° E). This facility was in support of the implosion bomb programme. There was a small control building and a firing stand for implosion experiments. FXR heads were used. The Circle implosion team would come to Potchefstroom from time to time to conduct tests of plane wave generators and to make basic measurements.

The site was built in just three months in 1985. There was a bunker for personnel and diagnostics to protect them from explosion tests. There were ducts for the beam from FXR heads. At Potchefstroom the engineers learned to make argon candle balloons to use as flash bulbs to illuminate explosive tests.[97] Exposure times are so short in an explosive test that a framing camera cannot see the test without illumination. The argon candle, powered by about 600 grams of high explosive, provides an intense flash to illuminate the scene. This also exercises the electronics engineering team to develop critical timing that would be valuable later to time a neutron generator.[98]

The most ambitious experiment at this site took place in 1990. The team decided to do a test in which a small-scale imploding high-explosive sphere would attempt to crush a small aluminium ball, about 2.5 kg. The aluminium was surrounded by two pressed PBX hemispheres. The team had a firing set that was only powerful enough to set off six detonators at once, but this was enough for six-point symmetry. This was a so-called octahedral sphere because six points on the surface create eight quadrants of equal size. The inner aluminium sphere is known as a 'witness ball'. If the six detonators fire simultaneously, then the shocks they produce in the high explosive will leave six symmetrical dents on the surface of the ball. Lack of symmetry indicates lack of simultaneity.

The event attracted VIP visitors and the device was detonated. The ball was never found but the explosion set off a brush fire and all personnel had to flee.

The IAEA visited the site and collected a fragment of imbedded shrapnel and had it environmentally tested for radioactivity. There is no point in sampling earth: dirt samples are nearly useless for determining uranium with accuracy if the uranium is natural. Surprisingly, the metal bit came back slightly contaminated with uranium-235—HEU. This was definitely not expected.[99]

The South African counterparts were questioned about this. The questions were designed not to reveal the conundrum the IAEA had found. Hopefully the questions were not leading. South Africa explained that the metal parts used in the Potchefstroom event had been machined on the same lathes in Circle that had been used to machine HEU. That adequately resolved the issue without revealing the reason for concern.

[97] Davis, W. C. et al., 'Explosive-driven shock waves in argon', *Proceedings of the 13th International Detonation Symposium* (Los Alamos National Laboratory: Los Alamos, NM, 2006), pp. 1035–44.

[98] Davis et al. (note 97).

[99] See e.g. Mayer, K., Wallenius, M. and Varga, Z., 'Sample characteristics and nuclear forensic signatures', ed. V. Fedchenko, SIPRI, *The New Nuclear Forensics: Analysis of Nuclear Materials for Security Purpose* (Oxford University Press: Oxford, 2015), pp. 93–127, pp. 117–22.

Pretoria Metal Pressings

PMP was never part of the nuclear weapon programme despite being adjacent to Advena. Much of the equipment from the dismantled programme and some key personnel went to PMP in the 1990s.

9. The end of the programme

An important task in ending the nuclear weapon programme was documentation. There were parts of seven nuclear assemblies to dismantle, inert test models, extra HEU and scrap, hundreds of non-nuclear components, and thousands of pages of documents ranging from technical drawings to government policy.

Staff members and engineers at Circle and Advena attended to the physical destruction of weapons and technical documentation. In 1991 the HEU was removed from the weapons, re-cast into ingots and returned to the AEC at Pelindaba.[100] The nuclear weapons remained intact, without HEU, in storage at Circle as a hedge to allow a return to an active programme. In 1993 the decision was made to dismantle the weapons and destroy much of their functionality. For example, steel parts, such as the gun barrels, were cut up in such a way as to make them unusable, but they remained in storage and could be useful models if there were a new programme. There was not a carefully documented programme to dispose of non-nuclear materials or machinery. There were many pieces that could be observed months after the programme officially ended—such as gauging parts in the measurement laboratory and odd pieces in the workshops. Specialized equipment for the programme was eventually removed and given to other Armscor entities such as PMP and Denel Aviation.

A number of documents were rewritten to exclude classified materials and preserve knowledge for commercial purposes. In a similar process, a drawing of the conceptual lighting system for an imploding sphere appeared on a sales brochure for applications of Advena's five-axis mill.[101] The subject of the drawing was not revealed in the brochure: it was used only to show the ability of the mill to execute a complex milling job.

One part of the dismantlement of the programme was carried out carefully and documented: the return of the HEU to Pelindaba. To oversee that process, an independent auditor was appointed to observe completeness: Wynand Mouton, a respected South African physics academic.[102] Mouton was not involved in designing the dismantlement process, only in auditing the results. He largely limited himself to the removal of HEU from the weapons and the return to the AEC. That important task seems to have been carried out well. Mouton did not oversee the destruction of non-nuclear components. That process was haphazard. Many parts were simply not destroyed, just put in storage, such as the tungsten–copper tamper pieces. Others, such as the gun barrels, were damaged beyond re-use but not further destroyed.

Mouton also did not oversee the effort to destroy technical documents related to the physics and engineering, such as those containing knowledge of the implosion

[100] von Baeckmann et al. (note 14).

[101] This document was one of the ones lost when the IAEA destroyed the day-to-day inspection files, notes and photographs in 2009.

[102] 'The dismantlement of South Africa's nuclear weapons' (note 13).

or boosting programmes.[103] These programmes did not lead to results or were not used in any actual weapons and were judged not to be sensitive. In addition, Circle retained a complete set of manufacturing documents for each actual nuclear device. These included dates of manufacture, deviation specifications, maintenance and eventual destruction. These documents were preserved to give outside observers, such as the IAEA, tangible evidence of the existence of the programme that had been dismantled months before.[104]

The dismantlement task was assigned to the Circle engineers because they had the weapons and most of the hardware. They focused on mechanical tasks. They paid little or no attention to computers and computer codes. They spent little time examining and destroying records at the AEC—the only main actor that was not under the control of Armscor. In the end the HEU was carefully removed. The weapons themselves were broken up haphazardly but certainly beyond re-use. The end of the programme was complete and the better qualified personnel scrambled to find new jobs as quickly as they could.

[103] Stumpf (note 3), section 5.3.

[104] von Baeckmann et al. (note 14); and International Atomic Energy Agency, GOV/2684 (note 16), annex 1.

10. Conclusions

From approximately 1970 to 1991 South Africa pursued a nuclear weapon programme. The programme was the brainchild of civilians and was largely a civilian effort from start to finish. The programme succeeded in building six nuclear explosive devices with a seventh nearing completion. A South African colleague summarized the programme as follows: 'They did it because they could', not because it was necessary or useful.

Many observers attribute the programme's end to the far-reaching political changes introduced by President F. W. de Klerk upon his election in 1989. This is really only a part of the story. The weapon programme was conceived as South Africa was increasingly isolated due to apartheid and on the verge of war with neighbouring states, particularly Angola supported by Cuban troops. Aircraft-carried nuclear weapons were tactically and strategically unsuited for use in deterring the Angolans. But even if they had been, the managers of the nuclear weapon programme failed to deliver a single usable product to the SADF during the critical years from 1982 to 1988. It was not until 1989 that the SADF had access to seven crude devices, one of which was only useful for an underground test and another never completed. Even the five weaponized devices varied in their military specifications. This was after South Africa had reached a ceasefire with Angola.

In fact, it was in 1985, well before the election of de Klerk, that the government decided to cap the nuclear weapon programme at seven gun-type devices and end the extremely expensive production of highly enriched uranium. It is easy to believe that the decision to cap the programme was accompanied by a determination to finally get the seven devices after a decade of delays.

Throughout the programme there were several main players. The Atomic Energy Corporation was run by civilians with a classical understanding of nuclear technology circa 1970. They were largely scientists and nuclear engineers. They understood nuclear power, including uranium enrichment and nuclear fission, and they knew that advances in nuclear technology can bring energy independence. They also understood what mastering nuclear fission and the uranium fuel cycle can mean in terms of the proliferation of nuclear weapons that took place in those first three decades of the nuclear age. They watched the big powers develop boosted implosion bombs and thermonuclear devices. The AEC's earliest plans naively assumed that they would follow the same path over the next 20 years. Their approach to the problem was scientific and not politically savvy. Their poor security precautions for an unnecessary nuclear test caused the government extreme embarrassment.

This caused the government to hand over the programme to the next player—Armscor—which created the Circle facility under the management of Kentron. The Circle staff had a completely different orientation to that of the AEC. They were mechanical and aerospace engineers. They understood reliability, quality, manufacturing and security. They did not understand physics. They were probably severely underfunded and struggled to produce a useful product. The desperate attempt to extend the life of the programme with the Advena implosion programme was too late and suffered from most of the same military and political disadvantages as the gun-type programme.

Finally, there was the SADF, which seemed more annoyed at an expensive programme that depleted precious financial reserves. It really had no use for the handful of weapons in its open-terrain warfare. Once the few nuclear weapons had been used, there would have been no back-up. Given the links back to the Soviet Union through Angola and Cuba, the southern tip of Africa could have become a nuclear battlefield. This was a losing strategy.

The programme did not fail due to incompetence. It was surprisingly robust. This was the effort of a white minority of barely 4 million people overseeing 30 million disenfranchised citizens. The engineering and execution of the programme showed genuine programmatic skills, albeit in a poorly funded environment. For example, South Africa achieved far more with its meagre resources in those years than Iraq did writing endless cheques to its scientists from oil income.[105]

In the end it was poor communications, poorly defined goals, and the radically different cultures of the scientists, the aerospace engineers and the military that doomed the programme. That makes it an especially interesting example: the only country to produce nuclear explosives, give them up voluntarily, join the NPT and submit itself to full IAEA safeguards.

Circles within circles

The initial driving force behind the nuclear programme was top-rank politicians and government officials, around 1970. They began initially with a desire to mine and sell uranium. Then they conceived the idea of enriching it in South Africa to add value to the sales. They authorized an expensive and inefficient indigenous enrichment programme because no other country would sell South Africa enrichment technology. Elements within the government then realized that, if they could enrich, then they could make nuclear explosives. The original justification for a peaceful mining explosive was quickly overtake by the idea of a weapon. Decision-makers at the top level were not concerned with details like yield or military utility; they just wanted South Africa to be an independent regional nuclear power.

The government created a nuclear programme at the Pelindaba nuclear research centre. The well-educated scientists of the Reactor Development Division there understood the concept of nuclear weapon programmes as implemented in the five nuclear weapon states, especially the United States. They understood a basic progression from crude weapons, to boosted weapons, plutonium production, implosion and eventually thermonuclear weapons. The RDD started with the crudest of concepts—a gun-type weapon—and never advanced past this stage. The

[105] Kelley, R. E., 'The Iraqi and South African nuclear weapons programs: The importance of management', *Security Dialogue*, vol. 27, no. 1 (Mar. 1996).

RDD was also not concerned much with military utility or details like explosive yield. They accepted the challenge of producing a nuclear explosion in the absence of close cooperation with the SADF.

From 1979 the programme was implemented by engineers with no physics training at the Circle facility, managed by Kentron for Armscor. This was a production task with little or no innovation or improvement over the design from the RDD. The RDD was excluded from the Circle activities. RDD scientists who had worked on the original design, and advanced concepts such as a boosted gun-type weapon, lost interest in a classified programme that was a career dead end. The RDD's concepts for a plutonium- and tritium-production programme died. Circle was slow to produce the required nuclear stockpile despite an increasing supply of HEU. Nevertheless, it was clear that Circle would soon work itself out of a job because the government was intent on ending the programme with a stockpile of only six usable weapons.

There were innovators at the higher levels of Armscor who were largely unconcerned with the details of the struggling Circle facility. These Armscor leaders were interested in a new and advanced nuclear weapon. Armscor was building IRBMs and there was not much point in such weapons in southern Africa without a nuclear warhead. They also had a financial programmatic incentive to develop an advanced weapon. When Circle completed its task, the programme would end and a lot of people would become redundant. The higher-level people at Armscor were the ones who conceived of 100-kiloton-yield weapons that would be largely targeted at cities and not military targets. There is no sign that the military encouraged such targeting. This task was the incentive to build Advena and develop implosion weapons. Money to build Advena was allocated but the advanced weapon programme never really started.

The silent partner in this story is the SADF. Its influence over the programme was never clear. It is likely that it regarded the six nuclear weapons as a liability more than an asset.

Government leaders, such as President P. W. Botha, were facing very different constraints than the enthusiastic apartheid leaders of the 1970s. South Africa was clearly undergoing huge political and social changes. There was no value or necessity to claim that South Africa was a regional nuclear-armed state; quite the opposite. They reversed the decisions of 1970 and ended the programme before massive political shock in the country.

Key findings

In closing, it is worth highlighting the key findings on the South African nuclear weapon programme.

South Africa managed to produce about six gun-type nuclear explosive devices before 1989: one demonstration device, five complete devices and one unfinished device. They used crude, early World War II technology. While South Africa claimed to have made about one device per year in the 1980s, in fact most of the weapons were completed in 1988 and 1989.

A key finding for military analysis is that the South African weapons were designed to be interchangeable between a glide bomb and a missile re-entry warhead. Their yield was not a specified military characteristic, but safety and security were paramount to military and government officials. Alongside the gun-type weapon programme, there was a parallel, but unsuccessful, effort to develop a more modern nuclear explosive using implosion technology.

South Africa dismantled the devices and acceded to the NPT in 1991, before acknowledging the existence of the programme in 1993. The IAEA made visits to South Africa in 1993 and essentially confirmed that South Africa's declarations concerning the end of the programme were correct.

Facilities near Pretoria, especially Pelindaba, Cirlce and Advena, have been credited with most technical responsibility for the programme. However, the Somchem facility near Cape Town was a key supplier of gas centrifuge technology (e.g. carbon fibre rotors) and was left with a larger reserve of technology (e.g. hydrodynamic calculation expertise related to implosion). The Pretoria facilities continued to support activities related to gas centrifuge enrichment even after the weapon programme ended. Circle was hot pressing samarium–cobalt magnets in 1993, and probably well before. This activity may have directly benefited the activities of the A. Q. Khan proliferation network when underemployed South African engineers were looking for new jobs.

Epilogue

South Africa's nuclear weapon programme caused South Africa to be under special scrutiny for a decade after the 1993 inspections. In 2004 the IAEA undertook a special mission to revisit all of the key sites of the programme. This included those that were capable of supporting the programme but were never involved in the earlier days. Visits to Pelindaba, Advena, Circle, PMP, Somchem and Naschem took place. Equipment was reinspected. Personnel were interviewed. It was clear that the original programme had been dismantled and its parts distributed to other industries. Capable sites were not engaged in any visible nuclear activity.

With this 2004 visit, the special monitoring ended. South African safeguards became normal again and IAEA could say with confidence that the programme was clearly gone. Finally, in 2010 the IAEA drew its formal broader conclusion that all nuclear materials and facilities in South Africa were in peaceful activities: it found no indication of the diversion of declared nuclear material from peaceful nuclear activities and no indication of undeclared nuclear material or activities.[106] This milestone was truly the end of this remarkable episode.

[106] International Atomic Energy Agency (IAEA), 'Safeguards statement for 2010', 2011, p. 6.

Appendix. Timeline of the South African nuclear weapon programme

Date	Event
1960s	Indigenous research on enrichment of uranium and a plutonium production reactor (Pelindaba)
1970	Uranium Enrichment Corporation of South Africa (UCOR) formed
1970s	Peaceful nuclear explosive (PNE) programme considered
1973	Lithium isotope separation studies begin
1974	Nuclear explosive programme authorized
	A nuclear test site authorized
	First stages of enrichment plant (Y Plant) completed
1975	Cuba with Soviet support actively joins the Angolan Government in the war with South Africa and Angolan rebels
1976	First nuclear test shaft completed
	Work on Pelinduna indigenous heavy water reactor terminated
	US fuel supply for SAFARI-1 reactor stopped
1977	Four containers of tritium received from Israel
	Y Plant cascades come into operation
	Second nuclear test shaft completed
	First full device produced by AEB from depleted uranium
	'Cold test' of a nuclear device underground planned to exercise all capabilities; stopped because of detection by a satellite
1978	Second device built without HEU
1979	Detection of a possible nuclear test in the South Atlantic by a US satellite
	Programme transferred to Armscor management
	Second device rebuilt with HEU
	RDD designs Circle facility for Armscor
1980	RDD constructs tritium handling facility at Pelindaba
	Armscor begins building Circle facility as dedicated nuclear weapon programme centre
1981	Circle facility completed and operational for Armscor
	Goriqua programme to build a military production reactor on south coast initiated by RDD
1982	First device built entirely at Armscor Circle building
	Peak of activity for a tritium-boosted bomb
1983	Programme to separate lithium isotopes using laser isotope separation begins
1985	Government formally decides to limit the programme to 7 gun-type devices
	Goriqua reactor project terminated
	Planning and activities on tritium-boosted device stopped
1986	Design of Advena factory buildings starts
1987	Small programme to develop commercial tritium products at RDD Pelindaba
1988	SADF suffers aircraft losses and cannot engage outside its borders
	Advena site commissioned (April)
	First fully weaponized and aircraft-deliverable production devices completed (June)
1989	South Africa stops producing HEU and weapons (February)
	Ceasefire in Angolan War (June)
	Major buildings completed at Advena without all equipment
1990	Largest 'cold test' at Potchefstroom
	President F. W. de Klerk announces that South Africa will become a responsible member of the international community; secret decision to dismantle

1991	HEU removed from nuclear devices and returned to Pelindaba AEC in non-weapon form
	South Africa accedes to the 1968 Non-Proliferation Treaty and CSA with the IAEA enters into force
	Half of Advena's workforce laid-off
1992	Last tritium withdrawn for commercial lighting programme
	All nuclear weapons preserved intact except for removal of HEU
1993	Non-nuclear components largely disabled along with most documentation
	Independent auditor declares programme certifiably destroyed (23 March)
	de Klerk publicly announces existence of a dismantled nuclear weapon programme (23 March)
	IAEA visits result in a completeness report confirming South African declarations
1998	South Africa ratifies the African Nuclear-Weapon-Free Zone Treaty (Treaty of Pelindaba)
1999	South Africa ratifies the Comprehensive Nuclear-Test-Ban Treaty (CTBT)
2002	Additional protocol to the CSA enters into force
2004	IAEA undertakes a special mission to revisit all of the key sites of the South African programme
2010	IAEA reaches broader conclusion that all nuclear materials in South Africa remain in peaceful use

AEB/AEC = Atomic Energy Board/Corporation, CSA = comprehensive safeguards agreement, HEU = highly enriched uranium, IAEA = International Atomic Energy Agency, RDD = Reactor Development Division, SADF = South African Defence Force.

Sources: Compilation based on author notes and e.g. von Baeckmann, A., Dillon, G. and Perricos, D., 'Nuclear verification in South Africa', *IAEA Bulletin*, vol. 37, no. 1 (Mar. 1995), pp. 42–48; and Masiza, Z., 'A chronology of South Africa's nuclear program', *Nonproliferation Review*, vol. 1, no. 1 (fall 1993), pp. 34–53.

About the author

Robert E. Kelley (United States) is a veteran of the United States' nuclear weapon programme, where he worked at the Nevada test site and the Lawrence Livermore and Los Alamos national laboratories. His career then shifted to investigation of nuclear weapon proliferation worldwide, especially in the former Soviet Union. He joined the post-war inspection team in Iraq in 1991, and then joined the International Atomic Energy Agency (IAEA) as a director of its Iraq Action Team. When South Africa disclosed its previously secret nuclear weapon programme in 1993, he was seconded by the US Government to handle the weapon analysis. He subsequently worked on remote sensing and nuclear intelligence for the US Government and again as an IAEA director in the run-up to the Iraq War. He has carried out specialized inspections in countries as diverse as Libya, Egypt, Syria, the Democratic Republic of the Congo, South Africa, Taiwan and South Korea. Since retiring, he has continued to write for *Jane's* magazines and SIPRI.