Chapter 3 Getting Highly Enriched Uranium

Following the government decision in 1969 to build a pilot uranium enrichment plant, the Atomic Energy Board had to dramatically scale up from an enrichment research program to an industrial program.[1] It had to find and hire many qualified personnel, accelerate the planning of the new plant, overcome engineering problems, engage in massive procurements domestically and abroad, and start large-scale manufacturing operations for the components of the plant.

Although the enrichment project was shrouded in intense secrecy, the government decided that such a large construction project could not be hidden for long. In July 1970, then Prime Minister John Vorster announced in Parliament that South Africa intended to build a pilot enrichment plant based on a "process which is unique in its concept."[2] Many countries and experts skeptically greeted Vorster's announcement, questioning South Africa's ability to develop an enrichment technology on its own.

Not until 1975, when senior South African nuclear officials presented a paper to a European Nuclear Conference in Paris, did South Africa provide partial information about its enrichment process.[3] However, the South Africans did not reveal details about the separating element until the late 1980s.[4]

In his 1970 announcement, Vorster emphasized that the enrichment plant was for peaceful purposes only. One goal of the project was to sell enriched uranium overseas, and Vorster invited any non-communist nation to collaborate in exploiting this new process for civilian, peaceful purposes.[5]

Vorster also stated South Africa's willingness to place all its nuclear activities under IAEA safeguards subject to the following conditions:

- South Africa would in no way be limited in the promotion of the peaceful application of nuclear energy;
- South Africa would not run the risk that details of the new enrichment process might leak out as a result of the safeguards inspection system; and

[1] A. R. Newby-Fraser, *Chain Reaction: Twenty Years of Nuclear Research and Development in South Africa* (Pretoria: Atomic Energy Board: Pretoria, 1979), p. 102.
[2] Newby-Fraser, *Chain Reaction*, op. cit., p. 93.
[3] A. J. A. Roux and W. L. Grant, "Uranium Enrichment in South Africa," *Nuclear Energy Maturity*, Proceedings of the European Nuclear Conference, Paris, April 21-25, 1975. See also Newby-Fraser, *Chain Reaction*, op. cit., p. 106; and Manson Benedict, Thomas H. Pigford, and Hans Wolfgang Levi, *Nuclear Chemical Engineering* (New York: McGraw-Hill Book Co., 1981), pp. 888-95.
[4] Interview with Anthony Jackson, February 1994. See also Daniel Kemp, Pieter Bredell, A. Albert Ponellis, and Einar Ronander, "Uranium Enrichment Technologies in South Africa," Atomic Energy Corporation of South Africa, Ltd., Paper presented at the International Symposium on Isotope Separation and Chemical Exchange Uranium Enrichment, October 29 – November 1, 1990, Tokyo, Japan. Whether the element itself is actually declassified is unclear. On a 1994 visit to the Y Plant, one of the authors was first told by senior safeguards officials that he could not see the separating element because it was secret. But another senior official allowed him to examine one.
[5] Newby-Fraser, *Chain Reaction*, op. cit., pp. 92-94.

- The safeguards system, while efficient, would be implemented on such a reasonable basis as to avoid interference with the normal efficient operation of the particular industries.

While not an outright refusal to accept safeguards and the associated Nuclear Non-Proliferation Treaty (NPT), Vorster's announcement appeared to signal that South Africa regarded its nuclear capabilities as a potential bargaining chip.[6] It was "not willing to open up all of its activities to an international community that seemed increasingly hostile to the country and its racial policies."[7] However, this conditionality also suggests that a nuclear weapons arsenal may not have been inevitable in 1970.

Still, Vorster did not mention that peaceful purposes included peaceful nuclear explosives or that the enrichment plant was being designed to make weapons-grade uranium in addition to low enriched uranium (LEU). LEU has the level of enrichment most often associated with overseas exports of enriched uranium and a civil purpose. Weapons-grade uranium is associated with nuclear weapons. If Vorster had been more forthcoming, the international outcry could have been far more pointed.

This deliberate omission fooled many in the international community, who took Vorster's announcement literally and assumed wrongly that the Y Plant would not make weapons-grade uranium. The US government wrote to a Congressional oversight committee that as late as 1976 "all information available to us indicates that the South African enrichment plant is designed for and intended to produce only slightly enriched uranium."[8] Although this view was not a consensus view in the United States intelligence community, South Africa had created ambiguity about the purpose of its unsafeguarded nuclear facilities and its refusal to sign the NPT.

Over the following decade and half, many would use this ambiguity to argue in public and policy debates that South Africa did not have nuclear weapons but only a capability to make them. As pointed out by Frank Pabian, the US expert on South Africa's nuclear program, "Once a threshold proliferant nuclear state has access to sufficient stocks of weapons-grade fissile material to make nuclear weapons, and a strong case can be made that they have requisite motivation to build nuclear weapons, the South African exemplar shows the likelihood that they will build nuclear weapons (and are not simply interested in only acquiring a 'capability' to build them at some distant point in the future."[9]

---

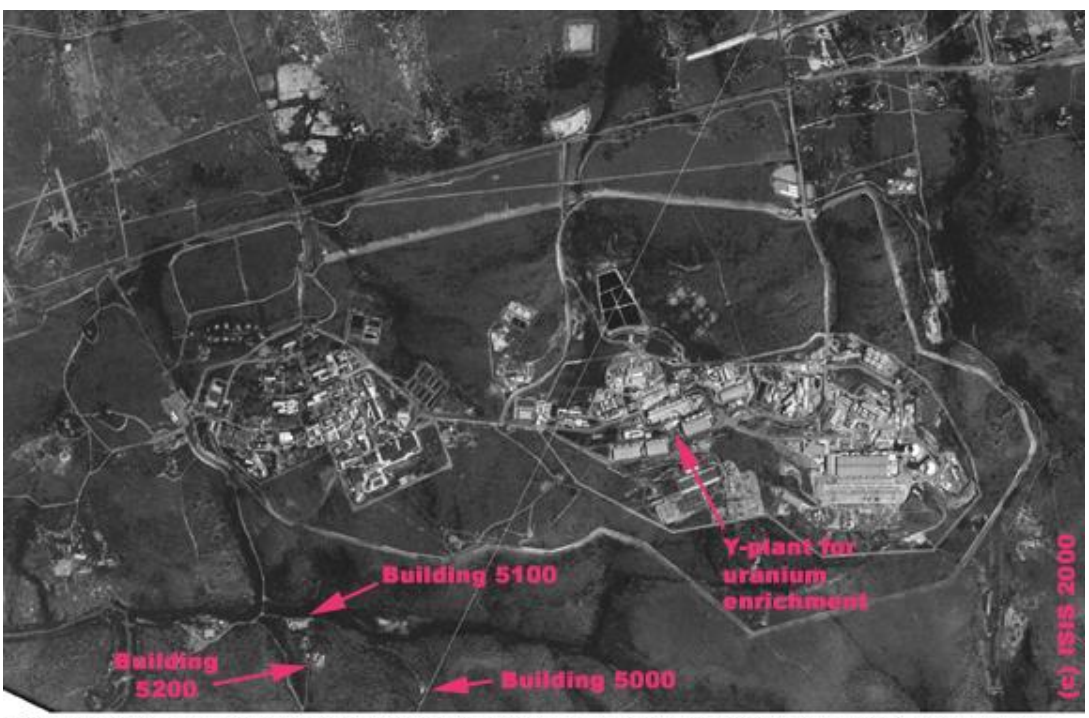
[6] Johann Viljoen and Deon Smith, *The Birth, Life, and Death of South Africa's Nuclear Weapons Program,* Unpublished manuscript commissioned by the Institute for Science and International Security, 1999.
[7] Viljoen and Smith, *The Birth, Life, and Death of South Africa's Nuclear Weapons Program*, op. cit.
[8] *Hearings on S. 1439 to Reorganize Certain Export Functions of the Federal Government to Promote More Efficient and Effective Administration of Such Functions*, before the Committee on Government Operations, US Senate, 94th Congress, 2nd session, January 19, 20, 29, 30, and March 9, 1976 (Washington: US Government Printing Office, 1976), pp. 1237-38; "Response to Senate Government Operations Committee Inquiry Dated July 15, 1975," from James T. Lynn, Director, Office of Management and Budget, Executive Office of the President, September 15, 1975, discussing the Y Plant.
[9] Frank V. Pabian, "The South African Denuclearization Exemplar," *Nonproliferation Review, 2015,* vol. 22, no 1, pp. 27-52. http://www.tandfonline.com/doi/full/10.1080/10736700.2015.1071969

Y Plant

One month after Vorster's announcement, South Africa passed legislation to establish a corporation for uranium enrichment. In November, the state-owned Uranium Enrichment Corporation of South Africa Limited (UCOR) was created, and Wally Grant became its first Managing Director and Ampie Roux its first chairman of the Board. The AEB's enrichment project staff was also transferred to UCOR.

A site adjacent to Pelindaba was selected as the site of the pilot enrichment plant, code named the Y Plant, and the ground for the plant was broken in November 1970. Figure 1 is a 1991 satellite image that shows the location of the Y Plant near the main Pelindaba site. Although the two sites were distinct, many services, such as security, transport, and library services, would be shared.

According to Newby-Fraser's 1979 *Chain Reaction*, the name of the site was derived by someone asking: "What happens here?" Others said: "This we do not talk about." In a similar manner as the name Pelindaba was selected, the new site was named Valindaba, a conjunction of two words common to many of the roughly seventy languages indigenous to the southern tip of the African continent. Individually, the words are "vala" meaning "to close" and "indaba" meaning the council. Together, the meaning of these two words is the "council is closed." By extension, Valindaba means "no talking about this."



Significant former nuclear weapons related facilities at the Pelindaba-Valindaba Complex, near Pretoria, South Africa. December 1991 KVR-1000 image from www.terraserver.com.

Figure 1 In this 1991 image, the Y Plant is visible; to the immediate left is the main Pelindaba nuclear site.

Newby-Fraser states that some cynically referred to the facility as “no comment.” Although this name did not last, he points out that the term is apt to describe the behavior of UCOR, which maintained extremely tight security over its activities. The 1970 law creating UCOR instructed the government to withhold from the public any information about the corporation and its activities that could be considered “contrary to public interest.”

Aerodynamic Enrichment Method

The South African aerodynamic enrichment process separates uranium isotopes through centrifugal effects created by the rapid spinning motion of a mixture of uranium hexafluoride gas and hydrogen carrier gas in a small stationary tube. An example of a separating element shown to one of the authors in 1994 by a senior South African enrichment expert was about five centimeters long and about one centimeter in diameter. The expert explained that the gas mixture enters at a high speed through tiny holes in the side of the tube and spirals down the tube. When the mixture reaches the holes at the ends of the tube, its radius of curvature is reduced several-fold, increasing the separation of the uranium isotopes.[10] The heavy fraction, more concentrated in uranium 238, exits to the side. The light fraction, more concentrated in uranium 235, exits straight out at the end. Because each separating element can enrich uranium only slightly, several separating elements are combined into “stages,” several thousand of which are linked together by pipes and valves into a “cascade.”

The Y Plant was organized into five consecutive enrichment blocks and one “stripper” section, each containing many stages. The blocks were located in three large buildings, named C, D, and E (see figures 2 and 3). Natural uranium was fed into block 1 in building C. The enriched product from block 1 (less than 2 percent uranium 235) went by pipe to blocks 2 and 3 in building D for additional enrichment up to 10 percent uranium 235. From there, pipes carried the enriched material to blocks 4 and 5 in building E, which discharged the final enriched product containing greater than about 80 percent uranium 235. Depleted uranium was discharged at the bottom of the stripper section in building C. Combined, all these blocks were referred to as one cascade, raising the enrichment level of the uranium from natural uranium, or about 0.7 percent, to 80 to 90 percent or more.

[10] See also Kemp, Bredell, Ponellis, and Ronander, “Uranium Enrichment Technologies in South Africa,” op. cit. Figure 1 in this paper shows this radial effect in a basic separating element.

Figure 2 Y Plant, with many high stacks, with main Pelindaba site in background. The tall stacks were part of a hydrogen ventilation system aimed at minimizing the chance of an explosion of hydrogen gas used in the enrichment process lines. Photo Credit: UCOR

The Y-Plant, closed in 1990, at the Valindaba site.
December 1991 image from www.terraserver.com.

Figure 3 Overhead image of the Y Plant

According to Anthony Jackson, a chemical engineer and the leader of the team responsible for the design and commissioning of the Y Plant, the attainment of an industrial production level required years of trial and error.[11] Learning to mass produce high precision separation elements and other key components for the enrichment plant was time consuming and expensive. "Money was the real issue," he added, because funding is necessary to "sort glitches out." Because the plant was for a "strategic" purpose, he said that funding to sort out all the engineering and chemical problems was never an issue. However, the difficulties of getting the process to work cannot be understated. The South Africans had to cope with many technological surprises, which delayed and reduced the accumulation of HEU.

In 1974 the commissioning of individual stages of the cascade started. By October of that year, initial enrichment started in block 3 of building D. The rest of the blocks were commissioned gradually, as development work continued. The full cascade was licensed for operation in February 1977 and the blocks were coupled together to start the run up to the production of 80 percent enriched uranium. After wide fluctuations in the enrichment level throughout the cascade during the first fifty days of operation, the enrichment level started to rise. After about 200 days of operation, the product reached 80 percent enrichment (see figure 4).

After start-up problems and the long equilibrium time of the plant, the first and relatively small withdrawal of HEU (80 percent enriched) at the product area occurred on January 30, 1978.[12] A few kilograms of 35 percent enriched uranium had been withdrawn from a lower section of the cascade at the end of 1977.

[11] Interview with Jackson in South Africa, February 1994.
[12] Waldo Stumpf, "South Africa's Nuclear Weapons Program," undated. See also Kemp, Bredell, Ponellis, and Ronander, "Uranium Enrichment Technologies in South Africa," op. cit.; and International Atomic Energy Agency (IAEA), *South Africa's Nuclear Capabilities* (GC(XXXV)/RES/567), IAEA document GC(XXXVI)/1015, Vienna, September 4, 1992.

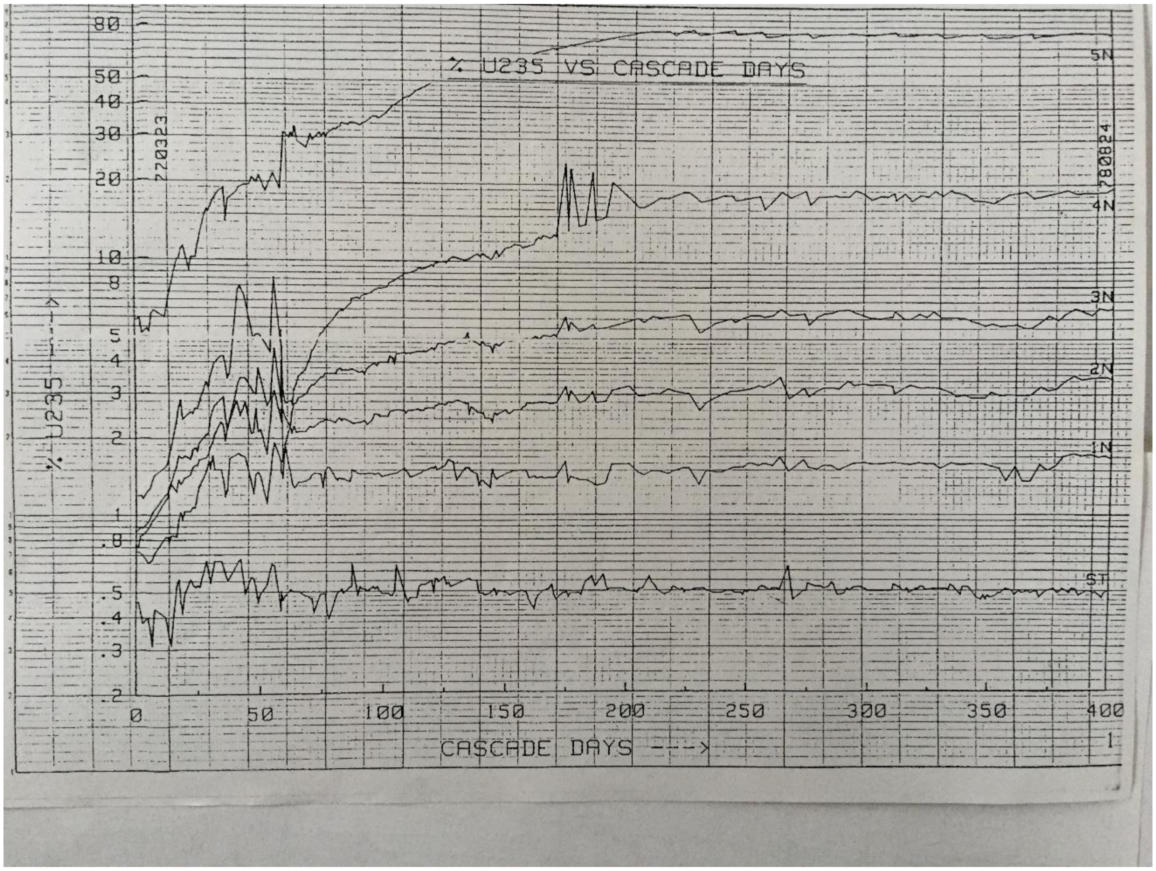


Figure 4 The graph, which is taken from the Y Plant's operational records, shows the daily enrichment level at the end of each of the five blocks and the stripping section. The names of the blocks are on the right of the graph and the enrichment level is on the left side on a logarithmic scale. The wide fluctuation in enrichment level is visible during the first fifty days of operation. Source: South Africa.

The Y Plant was designed to make roughly 100 kilograms of weapons-grade uranium per year and to have a nominal enrichment output of about 20,000 separative work units (SWU) per year.[13] Unexpected problems in the plant, however, restricted the enrichment level to about 80 percent during its first few years of operation and led to a production rate of only about half of its theoretical output.

By the end of August 1979, the plant had produced only about 64 kilograms of 80 percent enriched uranium during a period of 1.66 years. Nonetheless, this amount was enough for South Africa's first nuclear explosive, which was completed in November 1979.

The relatively small quantity of HEU produced means that the 1979 "flash" over the ocean south of South Africa picked up by the US Vela satellite could not have been a South African nuclear test. The lack of HEU does not exclude official South African participation in an Israeli test.

[13] According to Jackson, the output of the plant should have been about 20,000 SWU/yr.

Getting this 64 kilograms of 80 percent HEU was expensive and required the development of a large cadre of skilled engineers and scientists. By 1975, the UCOR project employed 1,200 people, and South Africa had already spent about 100 million Rand ($150 million in October 1974 dollars) on research and development on the enrichment program, excluding expenditures on the Y Plant.[14] By 1975, the cost of the Y Plant amounted to well over 50 million Rand ($75 million in October 1974 dollars).[15] A large proportion of the research and development funds was used to assist South African industrial firms to create the expertise and infrastructure necessary for the various sophisticated manufacturing tasks assigned to them.

About 235 different companies contributed their expertise and craftsmanship to the design and construction of the machines and instrumentation for the Y Plant.[16] In the process, South African companies enhanced their skills and abilities greatly, including importing significantly more sophisticated machine tools, equipment, and materials.

Sensitive work, including the manufacturing of the separation elements, the cleaning of all components, and the assembling of manufactured components, occurred at Valindaba. This work was conducted under tight security.

Foreign Procurement

Although South Africa has consistently said that the Y Plant was an indigenous effort, many key items for the plant were obtained from abroad. Foreign procurement was essential for the Y Plant to operate successfully without experiencing additional delays or complications.

This assessment is not meant to diminish the accomplishments of the South Africans, many of whom have bristled at the suggestion that the program was not indigenous. Although foreign assistance of many different forms was necessary, the Y Plant's success depended heavily on the skill and initiative of South Africa's scientists and technicians combined with the government's willingness to provide adequate resources and on-going support from the highest levels of government.

From the South African government's perspective, it would have been prudent in many cases to acquire an item from abroad rather than make it. In addition, South Africa did not have the industrial base to make all the necessary machine tools, sophisticated

---

[14] Roux and Grant, "Uranium Enrichment in South Africa," op. cit.; and Benedict et al., *Nuclear Chemical Engineering*, op. cit., p. 889.

[15] The figure for the Y Plant is taken from Barbara Rogers and Zdenek Červenka, *The Nuclear Axis* (New York: Times Books, 1978), p. 186. Waldo Stumpf, head of the Atomic Energy Corporation, stated that the total capital costs for the construction of the Y Plant amounted to 200 million Rand or $60 million at 1993 exchange rates. However, he did not make it clear whether that 200 million Rand figure included R&D costs or had been corrected to 1993 values of the Rand, which is the approximate date of his statement. See Stumpf, "South Africa's Nuclear Weapons Program," undated. If the 200 million Rand represents the actual uncorrected expenditures to build the Y Plant, then this value would correspond to about $300 million using the exchange rates in late 1974.

[16] Newby-Fraser, *Chain Reaction*, op. cit., p. 113.

equipment, and components. Thus, foreign procurement was necessary for many key items. In its quest to build and operate the Y Plant, South Africa participated in a range of questionable or illegal imports.

During the early 1970s, however, export controls on nuclear or nuclear-related components were nonexistent or weak by today's standards. As a result, few exports to South Africa were controlled. However, the growing anti-apartheid movement in the mid-1970s led Western governments to take action to limit nuclear exports to South Africa. This controversy also led to public revelations of many nuclear exports to South Africa.

The media at the time reported that South Africa acquired items for its uranium enrichment program from US, French, German, and Swiss companies.[17] Important instrumentation for measuring isotopic concentrations of uranium and compressors was imported from Germany. Valves and instrumentation for the enrichment plant were imported via circuitous routes, including Germany, according to a South African who was formerly a senior official in the enrichment program. Additionally, unsafeguarded uranium hexafluoride was imported from France, according to South African nuclear officials. This uranium hexafluoride was the first feed stock into the Y Plant.

In 1975 the US Senate's Government Operations Committee investigated an export of industrial-process computers to the Y Plant from the Foxboro Corporation.[18] Under a US Commerce Department license, Foxboro exported two computers and spare parts during 1971 to 1973 for a price of about $2 million. The licenses were in the name of UCOR, the South African agency responsible for developing the enrichment facility, and the stated purpose on the license was "operation of experimental facilities and pilot plants for nuclear research and development."[19] According to a Foxboro executive interviewed by the committee, the company knew that the computers were to be used for "some sort of uranium plant," although the South Africans were generally secretive.[20] Foxboro learned that the facility was a uranium enrichment plant during the installation of the computers despite South Africa restricting Foxboro personnel to the computer area of the plant and monitoring their activities closely.

According to a former member of the AEB and the nuclear weapons program, South Africa also arranged for foreign companies to build plants that would manufacture components for the enrichment plants. He said the Swiss companies Balzers and VAT built a factory in South Africa largely to make valves and pipes for the enrichment program.

---

[17] Frank Barnaby, "Nuclear South Africa," *New Scientist*, October 19, 1978.
[18] *Hearings on S. 1439 to Reorganize Certain Export Functions of the Federal Government to Promote More Efficient and Effective Administration of Such Functions*, before the Committee on Government Operations, US Senate, 94th Congress, 2nd session, January 19, 20, 29, 30, and March 9, 1976 (Washington: US Government Printing Office, 1976).
[19] *Hearings on S. 1439 to Reorganize Certain Export Functions of the Federal Government,* op. cit., p. 1232.
[20] *Hearings on S. 1439 to Reorganize Certain Export Functions of the Federal Government,* op. cit., p. 1226.

Another important supplier to UCOR was the South African trading company Krisch Engineering (Pty) Ltd, which would later become an important cog in the proliferation network operated by the Pakistani A.Q. Khan. At the time, Krisch was the local agent for the German firms AEG Telefunken and Leybold Heraeus GmbH. It supplied important vacuum equipment to UCOR during the 1970s and early 1980s. Krisch also arranged the manufacture of a highly specialized prototype valve at Leybold Hereaus for the South African enrichment program.[21]

The enrichment program, however, was unable to get everything it needed. For example, a senior member of the enrichment program said in a 1994 interview in South Africa that the program was thwarted in its efforts to obtain special seals for where the rotating shaft enters a compressor. The seal must have extremely low leak rates that can prevent the ingress of oxygen, moisture, and oil, requiring specialized shaft sealing methods.[22] Unable to acquire the necessary components overseas, they were forced to develop the seals themselves, encountering many difficult problems in the process.

Becker Nozzle Process

Media reports and members of the African National Congress have asserted that the enrichment plant depended extensively on the jet-nozzle process developed by Erwin Becker and his colleagues at the Karlsruhe nuclear research center in Germany during the 1950s and 1960s. Roux responded to these types of critics: "While there may, in the very early days, have been common features, the UCOR process in its developed form is as far removed from any other enrichment process as the North Pole is from the South Pole."[23]

Becker, however, challenged South Africa's claim for uniqueness right after Roux and Grant delivered their paper at the 1975 European Nuclear Conference. Becker said at a press conference that he had collaborated closely with the South Africans insofar as they had been given the freedom of his research facilities at Karlsruhe.[24] South Africa did not return the courtesy, he noted. On a visit to Valindaba in 1974, he was not allowed to see the separating element or the process equipment. Nonetheless, at the 1975 press conference Becker had to concede that not all the details of the two approaches are the same.[25]

---

[21] *Summary of Substantial Facts*, in the High Court of South Africa, the State versus Daniel Geiges and Gerhard Wisser, undated. See also Albright, *Peddling Peril* (New York: Free Press, 2010).
[22] P. Mayfarth, "Special Compressors for Uranium Enrichment," *Sulzer Technical Review*, April 1986.
[23] Newby-Fraser, *Chain Reaction*, op. cit., p. 111.
[24] David Fishlock, "South African Energy," Report prepared for the Congressional Research Service of the Library of Congress, September 1976. At the time, Fishlock was Science Editor at the London *Financial Times*.
[25] Quoted in Fishlock, "South African Energy," op. cit.

In 1977 Becker reissued his allegation and went further. He said that Roux and other South African scientists had free access to his research and may have succeeded in adapting it.[26]

Both processes are based on the high performance stationary walled centrifuge. Becker's group had avoided using the term "centrifuge" to avoid potential problems with German classification rules that in 1960 had been amended to make all work on gas centrifuges secret.

The Becker and UCOR processes do differ, however. A widely discussed difference is that UCOR developed an ingenious cascade technique, the "helikon" process, which, in combination with the separation element, can be considered a unique process.[27] However, the helikon technique was not deployed in the Y Plant, but in the later semi-commercial Z Plant at Valindaba.

Waldo Stumpf, the head of the Atomic Energy Corporation in the late 1980s and 1990s, which was the immediate successor to the AEB, said in an interview in 1994 that the Germans never solved the problems posed by the mixture of uranium hexafluoride gas and hydrogen gas, which posed many unique challenges in successfully operating the Y Plant. He said that the Becker-nozzle plant that Germany sold to Brazil in 1975 was going to use helium instead of hydrogen. One of the problems posed by hydrogen is that it is explosive in the presence of oxygen. With so much hydrogen in the process gas, the risk of explosion existed within the cascade piping and equipment. South Africa had to institute a variety of measures to keep air out of the cascade and ensure proper ventilation of any hydrogen that escaped the cascade into the atmosphere. The tall stacks visible at the Y Plant are part of that hydrogen ventilation system (see figure 2).

Steag

Another controversial issue is the nature of UCOR cooperation with the German company Steag AG on a joint uranium enrichment endeavor between 1973 and 1976. Steag was a German energy group that controlled the patent rights to Becker's jet-nozzle process. Starting in 1970, Steag worked to develop the Becker nozzle technology for export and its application in commercial enrichment plants.[28] In 1974, Steag built an advanced prototype stage using the Becker nozzle, where all the major components were designed to facilitate serial production for a commercial-scale enrichment facility.

Its collaboration with South Africa followed Vorster's 1970 announcement of South Africa's willingness to cooperate with any non-communist country in exploiting its new enrichment process. Vorster's goal was to build a larger uranium enrichment plant in addition to the Y Plant. In this larger plant, South Africa intended to enrich its domestic

---

[26] Jim Hoagland, "S. Africa, With US Aid, Near A-Bomb," *The Washington Post*, February 16, 1977.
[27] See for example, Benedict *et al. Nuclear Chemical Engineering*; or W. L. Grant, J. J. Wannenburg, and P. C. Haarhoff, "The Cascade Technique for the South African Enrichment Process," *Developments in Uranium Enrichment, AIChI Symposium Series*, No. 169, Vol. 73, pp. 20-24.
[28] E. W. Becker, et al., "Physics and Technology of Separation Nozzle Process," *Nuclear Energy Maturity, Proceedings of the European Nuclear Conference*, Paris, April 21-25, 1975.

uranium and sell it overseas, realizing its long term goal of deriving greater economic value from the uranium it mined.

South Africa understood it could not build a commercial-size enrichment plant alone. It needed partners to share the financial risk and extend the guaranteed market for enriched uranium. In addition, the demands for manpower and manufacturing resources would be beyond South Africa's capabilities, and South Africa would need to rely heavily on the overseas partners in meeting these demands.[29] For overseas collaborators, the benefits would include financial rewards, fruitful scientific and technological collaboration, and an ensured supply of enriched uranium. The last benefit was appealing to several countries that wanted to lessen their then dependence on Russian and US enriched uranium supplies.

Despite high initial expectations, in 1976 Steag ended its collaboration with UCOR, citing disagreements over financial arrangements and the sharing of risks in building a commercial enrichment plant in South Africa. For example, South Africa insisted that Steag was to be financially responsible for any failures in supplies of equipment caused by the worsening international political situation, i.e. growing pressure to impose economic sanctions on South Africa because of its apartheid policy.[30]

South Africa maintains that in the end the two sides conducted only joint feasibility studies on a plant that would produce several million separative work units per year.[31] The goal was to compare the South African and German processes to determine which system was more feasible technically and more viable financially as part of deciding what type of plant to build. *Chain Reaction* maintained the study showed that the South African process could form the basis of a competitive enrichment plant.[32]

The Anti-Apartheid Movement of Germany charged that the collaboration was far more extensive. These charges were laid out in the 1978 book *Nuclear Axis* by Barbara Rogers and Zdenek Červenka. Based on a set of secret documents obtained by the Anti-Apartheid Movement of Germany from the South African embassy in Bonn in 1975, *Nuclear Axis* argues that South Africa received the jet-nozzle process from Steag during this collaboration and this transfer essentially became the UCOR process. The authors claim that the process announced by Vorster in 1970 was not the aerodynamic process, and failed in any case soon afterwards.

The documents show that Steag and the West German government wanted to establish an extensive collaboration with South Africa on an enrichment plant, despite growing public and international opposition to any kind of nuclear and military cooperation with South Africa. But the documents provide only indirect support for the authors' charges that Steag supplied South Africa with its secret jet-nozzle process. The documents indicate that Steag intended to grant UCOR an option for a sublicense for the manufacture of the

[29] Newby-Fraser, *Chain Reaction*, op. cit., p. 105.
[30] Barbara Rogers and Zdenek Červenka, *Nuclear Axis*, p. 207, citing *Japan Times*, August 8, 1970, p. 84.
[31] Newby-Fraser, *Chain Reaction*, op. cit., p. 105.
[32] See also Roux and Grant, "Uranium Enrichment in South Africa," op. cit.

jet-nozzle process. Because the South Africans viewed obtaining this sublicense an "essential pre-condition" for the start of a comparative economic study, *Nuclear Axis* concluded incorrectly that the comparative study was actually a technology transfer of the jet-nozzle process that would form the heart of the UCOR process.[33]

The West German government challenged the claims in the *Nuclear Axis* and denied that any technology transfer took place. It also appears that the reason the West German government did not allow a transfer appears to have been in response to increasing public and international opposition to nuclear cooperation with South Africa rather than opposition to building a plant overseas. In late 1973, several members of the West German Cabinet opposed Steag's proposal for a joint comparative study for a uranium enrichment plant, fearing the harsh reactions of other African states.[34] Although the proposal did not include anything about actually building an enrichment plant, one member of the cabinet believed that the whole operation made sense only if the plant was built, a step he opposed.[35] The insistence on including a sub-license for manufacturing the jet nozzle in the proposal strengthened this cabinet minister's belief that they intended to build a plant in South Africa.

Despite the lack of support from the West German Cabinet, Steag and UCOR launched in early 1974 a joint comparative economic feasibility study between the Karlsruhe jet-nozzle process and the South African process. However, without German government backing Steag could not obtain funding for an enrichment plant.

Although *Nuclear Axis*'s claims of Steag providing the jet nozzle process to South Africa are not supported by the available information, German and other European companies provided key nuclear or nuclear-related assistance to South Africa's enrichment endeavors. One former South African nuclear official said that UCOR's expectations of its collaboration with Steag were clear. While attending briefings on the enrichment cooperation with West German companies and officials, he learned that South Africa expected that German companies would provide the technology to make a commercial plant work. How much this collaboration helped operate the Y Plant is unclear, especially given the differences in this plant and the planned commercial-scale plant. Nevertheless, the collaboration likely helped facilitate the movement of sophisticated goods to South Africa.

During its cooperation with German companies and laboratories in the 1970s, South Africa may have gained access to both unclassified and secret information about the Becker nozzle process, key suppliers, and methods of overcoming operational problems in operating a cascade. Such information may have helped South African scientists overcome their problems in building, equipping, and operating the Y Plant. Improvements in the separation elements in the mid-1970s, for example, may have resulted from such contacts.

---

[33] Rogers et al., *Nuclear Axis*, op. cit., pp. 70-74.
[34] Rogers et al., *Nuclear Axis*, op. cit., pp. 69-70.
[35] Rogers et al., *Nuclear Axis*, op. cit., p. 69.

Semi-Commercial Plant, or Z Plant

In 1975, despite the lack of clear support from Steag, South Africa decided to build a larger enrichment plant, which South African officials estimated would have a capacity of 5 million SWU per year. But without foreign partners, South Africa subsequently reduced the size of the plant. In the end, South Africa built a semi-commercial plant with a capacity of 300,000 SWU per year, large enough to provide LEU to two light water reactors that it ordered from France in 1976. The Z Plant, built next door to the Y Plant, exploited new methods, such as the helikon technique, which reduced its cost and improved its efficiency compared to the Y Plant. According to Jackson, the motivation was strategic, in the sense that South Africa's growing isolation made it more difficult to buy enriched uranium on the international market.

Construction on this larger plant began in 1979, and commissioning with uranium hexafluoride started in 1984. Because of problems resulting from insufficient prototype experience, enriched uranium production did not begin until 1988.[36] Afterwards, however, operation was not continuous. Problems with uninterruptable power systems and a special cooling system associated with uranium hexafluoride condensers led to the plant operating only about two months in 1990.

This plant produced 3.25 per cent enriched uranium, via batch recycling, for the twin Koeberg power reactors, which required about two-thirds of its optimum annual production of 300,000 SWU. Any spare separative capacity was intended to be sold on the world market.[37]

From 1988 until mid-1993, the semi-commercial plant produced 734,000 SWU, with 95 per cent supplied to the Koeberg reactors and the other 5 percent supplied to foreign customers.[38] The total output for these years corresponds to the production of about 189,000 kilograms of 3.25 enriched uranium at a tails assay of 0.3 percent. The average annual output during each of these five years was about 150,000 SWU per year, or about 38,000 kilograms per year of 3.25 per cent enriched uranium.

The enrichment process remained highly energy intensive and was not competitive with overseas producers, particularly in the oversupplied world enrichment market that existed in the early 1990s. With little prospect of economic viability, the Z Plant ceased operation on March 31, 1995.

Problems in the Y Plant

South Africa's efforts to find an international partner may have failed but they served to improve the enrichment program's knowledge of the aerodynamic method and opened

[36] Kemp et al., "Uranium Enrichment Technologies in South Africa," op. cit.
[37] J. Jones, "South Africa Enrichment Plant Now Commercial, AEC Head Says," *Nucleonics Week,* January 23, 1992.
[38] P. J. Ventor, "Prospects for the South African Front-end Nuclear Fuel Cycle Industry," International Conference on Enrichment, sponsored by the US Council for Energy Awareness, Washington, D.C., June 13-15, 1993.

doors to a variety of foreign high-tech goods that it needed to acquire for the Y Plant and later the Z Plant. This overseas assistance was critical to the success of the Y Plant, which was very much a pilot plant struggling to operate.

As the Y Plant fought to operate in the 1970s, it experienced many inefficiencies and problems. These problems remained hidden for years, emerging only after South Africa signed the NPT in 1991 and instituted a more transparent policy.

The plant's problems reached their peak during August 1979, which the Y plant workers call "chaos day." This unexpected event ended the production of 80 percent HEU for 23 months, until July 1981.

Chaos day resulted from greater than normal chlorine impurities in locally produced uranium hexafluoride feed, which in turn caused a massive chemical reaction in the uranium gas and the hydrogen carrier gas. According to Jackson, the result was solid uranium depositing on the inside of the cascade, reducing the output of the top end of the plant to less than 10 percent instead of 80 percent enriched uranium. The 23-month renovation included the replacement of all the old separating elements whose holes had become blocked. After restart and the reestablishment of equilibrium operation, the plant finally started producing HEU (but still only 80 percent enriched) at the end of July 1981.

Chaos day was the surprise finale of a rash of problems in the Y Plant that had occurred after it started enriching uranium in 1974. These problems, some of which defied explanation, significantly complicated the plant's startup and then reduced its enriched uranium output. During this initial period, HEU output was only half of what was expected.

The first type of problem was due to inefficient mechanical processes in the Y Plant cascade, which stretched throughout the blocks, which led to the enriched and depleted streams combining again after leaving the separator elements, commonly called "mixing." The Y Plant did not use the more advanced helikon technique, which significantly reduced mixing in the semi-commercial plant. It used a "Pelsakon backpump cycle" which, according to Jackson, did not work as well as expected, and resulted in a lower separative work output than expected.[39] Initially, the mixing loss in the backpump phase of the cycle was assumed to be 10 percent. In practice, however, mixing losses were considerably higher.

The plant also suffered from an unexpected loss of separating capacity. The cascade was unavailable more than expected. Impurities, particularly nitrogen, leaked into the process gas, causing additional losses. Over time, the separating elements did not work as designed because of blockages and other problems.

---

[39] The Y Plant had a complicated operating cycle, which included batch recycling, permitting total reflux at different parts of the cycle, and a complicated Pelsakon gas pumping system (pumping gas forward, then holding it before back-pumping the gas briefly).

The third loss mechanism involved catalytic chemical reactions between uranium hexafluoride and hydrogen gases.[40] During the first several years of operation of the Y Plant, project personnel spent a great deal of time trying to reduce the loss of enriched uranium from chemical reactions. In 1977 South African officials stated: “Detailed studies in the laboratory backed by extensive plant experience have given the background information on the conditions to be maintained if uranium hexafluoride losses are to be kept below acceptable limits.”[41]

Starting in the late 1960s, the enrichment project realized from open scientific literature that the reaction of uranium hexafluoride and hydrogen could cause the formation of solid uranium products and hydrofluoric acid (HF). However, the available public literature suggested that the reaction should occur only above a temperature of 125 centigrade, which was well above the maximum temperature in the Y Plant.

Yet, laboratory experiments in the early 1970s showed that the reaction would occur at much lower temperatures in systems simulating the Y Plant cascade. These systems, which were more complex than those described in the open literature also contained teflon filters, which looked like top hats and were used to filter dust from the rings of rotary compressors, some of which were quite large. The filters ensured that dust did not plug or otherwise damage the separating elements. After 500 to 4,000 hours, these systems exhibited a catastrophic catalytic reaction, where the reaction rate rose dramatically and HF concentrations increased rapidly. In terms of uranium hexafluoride gas concentration, after a slow decrease in the concentration, the gas concentration at the filter would quickly drop toward zero, signaling in essence the plugging of the filter by reaction products. On dismantling the test systems, the operators discovered that reaction products, which were a form of uranium tetrafluoride, were formed uniformly throughout the teflon filters.

Based on knowledge gained in the 1980s, the South African researchers concluded that this catalytic behavior resulted from chlorine contamination on the metal surfaces and in the teflon filter material. During the 1970s, without this knowledge, the plant operators solved the problem empirically. They polished the aluminum surfaces and conditioned the systems with HF and uranium hexafluoride. These steps increased the “incubation” period from 500 to 4,000-10,000 hours. The operators also learned that by replacing the filters, longer periods of stable plant operation could be achieved.

For example, the first block 3 prototype stage (located in building D and called “Maverick”) experienced this catastrophic loss rate after 500 hours. Operators stabilized Maverick’s operation by replacing its teflon filters.

---

[40] This discussion of chemical reactions is based, unless otherwise noted, on G. J. Leuner, *Summary Report on the Y Plant Chemical Loss Problem from January 1978 until August 1979*, Atomic Energy Corporation, South Africa, July 1993.

[41] A. J. A. Roux, W. L. Grant, R. A. Barbour, R. S. Loubser, and J. J. Wannenburg, “Development and Progress of the South African Enrichment Plant,” International Conference on Nuclear Power and Its Fuel Cycle, Salzburg, Austria, May 2-13, 1977, IAEA, IAEA-CN-36/300.

Subsequently, almost all the stages of block 3 which was the first one constructed, exhibited this catastrophic loss behavior with incubation periods between 1,000 and 4,000 hours. Replacing the filters and cleaning key equipment stabilized these stages. Because operators had learned to chemically clean the metal components, the stages in the other blocks rarely had catastrophic reactions after such short incubation periods.

However, losses from chemical reactions continued. According to Jackson, the plant experienced inexorable losses that were apparently a function of the effective surface area of the cascade, where the filters had a much higher effective surface area than pipes and other metal components.

From cascade day 200 until cascade day 733 (chaos day), for example, the plant withdrew only about half of the expected amount of 80 percent HEU (64 kilograms discharged vs. 130 kilograms expected). About 85 percent of this difference could be attributed to losses stemming from a range of chemical reactions and other losses of uranium material.[42] The chemical losses included catastrophic reactions on filters, non-catastrophic reactions on filters, and to losses during decommissioning and maintenance of stages. As of the early 1990s, no satisfactory mechanism was identified to explain the rest of the losses.

An unusual phenomenon occurred at the top end of the cascade, where the catastrophic reaction in the filters led to small greenish black agglomerations within the filter rather than a uniform distribution as in the lower blocks.[43] South African scientists did not identify the uranium products on these filters, and they could not reproduce this phenomena in the laboratory using natural uranium. They concluded that the most probable reason for the agglomerations was a combination of radiation chemistry effects associated with the higher radiation from HEU and the higher concentration of impurities at the top end of the cascade. In total, during this initial period prior to chaos day, about 13.5 kilograms of uranium 235 were estimated to have ended in these agglomerations in the filters in blocks 4 and 5, of which about 85 percent was in block 5.[44] This loss accounted for almost 30 percent of the total losses in uranium 235 experienced during this initial period leading up to chaos day.

Because of the relatively large amount of high quality HEU material deposited on filters in blocks 4 and 5, South Africa instituted a recovery program. Because these blocks contained only about 15 percent of the teflon filters, in the plant, the vast majority of the filters were stored without recovery. In total, these discarded filters contained a

---

[42] Mass balance considerations would provide a difference of 47.6 kilograms of uranium 235 that must be explained via losses. However, approximately 40.3 kilograms of uranium 235 could be accounted for from a variety of loss mechanisms. See *Summary Report on the Y Plant Chemical Loss Problem from January 1978 until August 1979*, op. cit.

[43] Because the total amount of uranium on the filters at the high end of the cascade was relatively small, the blackish green flecks were not that noticeable compared to the filters at the lower end where the filter would appear green when the filters system was dismantled. Initially, the reaction products were khaki in color but turned green on exposure to air.

[44] *Summary Report on the Y Plant Chemical Loss Problem from January 1978 until August 1979*, op. cit.

significant amount of enriched uranium that would ultimately take years to accurately measure.

Given all this experience with unexpected chemical reactions, why did chaos day occur? Why did the operators use untested domestically produced uranium hexafluoride? According to Jackson, although they did not know at that time that chlorine was the catalytic agent, he and others argued against using the new material. However, they were overruled.

After the August 1979 crash, the plant operators learned that a similar event could be prevented by using only high purity uranium hexafluoride and managing the reaction problem carefully. The conversion plant that turned yellowcake into uranium hexafluoride removed trace impurities at the end of the process rather than near its beginning. The uranium hexafluoride was sampled for impurities and any material not meeting rigorous specifications was recycled back through the purification process. Operators carefully measured the enrichment levels in the blocks and monitored the uranium buildup on the filters with a unique, highly collimated gamma-radiation detector. The result was that the operators could recognize when a filter was becoming overloaded with uranium and needed to be replaced with a fresh one before the catalytic reactions could get out of hand. In this way, the operators avoided another chaos day and reduced the losses from chemical reactions.

An inadvertent result of this careful record keeping was that the daily operating records were both detailed and maintained over the whole life of the plant. Later, chapter 10 will discuss how fortunate it was for the IAEA's verification effort in the early 1990s that South Africa preserved these records, particularly given the uranium losses in the Y Plant and the lack of accurate records about the amount of uranium in most of the teflon filters.

HEU Production

With the resumption of 80 percent HEU production in July 1981, the Y Plant started to significantly increase its output. It also started to make weapons-grade uranium, or uranium enriched over 90 percent, in late 1982. HEU production was further increased with the installation of improved enrichment separating elements.

Until the Y Plant shut down on February 15, 1990, it produced in total about 990 kilograms of HEU with an average enrichment of 68 percent. Table 1 shows the forms of this HEU and some information about its use. Table 2 lists the amount of HEU South Africa assigned to its major programs by 1991.[45]

[45] David Albright, *Highly Enriched Uranium (HEU) Inventories in South Africa, status as of end of 2014* (Washington, D.C.: Institute for Science and International Security, January 31, 2015). http://isis-online.org/uploads/isis-reports/documents/Highly_Enriched_Uranium_Inventories_in_South_Africa_November_2015.pdf

The South African nuclear weapons program received about 478 kilograms of HEU (average enrichment about 87.4 percent). Of this amount, about 88 kilograms ended up in scrap and were recycled, and about 6 kilograms were lost.

The other major program to which South Africa assigned HEU prior to the closure of the Y Plant was the US-supplied, 20 megawatt-thermal (MWth) Safari-1 reactor, located at Pelindaba. This program was assigned about 215 kilograms of HEU (average enrichment 46 percent by September 1991). About 85 kilograms of this HEU had been sent to the Safari reactor. About four kilograms of this HEU were lost during the processing of the fuel. The rest was stored.

Almost 170 kilograms of HEU were used to blend up stocks of low enriched uranium (LEU) for use in domestic power reactors. Of this amount, 92 kilograms were 90 percent enriched. This blending operation was done in the late 1980s, when South Africa had developed an excess of HEU for its nuclear weapons program. The second blending operation used HEU with an average enrichment of 28 percent that was drained from the Y Plant cascade after shutdown.

When South Africa signed the NPT in 1991, it had an HEU inventory of over 800 kilograms with an average enrichment of about 70 percent (see table 1). The vast bulk of this HEU was not irradiated and was in readily usable forms.

Table 1: HEU Production in the Y Plant, in kilograms

HEU Produced in Y Plant	HEU	U235	% U235 (average)
Shipped as uranium hexafluoride for further processing	515	437	85%
Shipped in the form of uranium bearing process filters for recovery	144	60	42%
Shipped in the form of uranium bearing powder for recovery	93	39	42%
Used for upgrading (blending) imported low enriched uranium (LEU)	92	83	90%
Used for upgrading (blending) domestic LEU	77	28	36%
Other(a)	72	30	42%
Total	**993**	**677**	**68%**

(a) This category includes HEU in additional scrap, cold traps, powders, and filters, and recalculated or re-estimated HEU quantities not included in the initial declaration given to the IAEA in 1991 but added prior to 1994 or 1995. A fraction of this HEU is difficult to recover economically into a usable form and is likely considered waste. Adjustments in the total HEU stock made after 1994 or 1995 are not included but are less than 100 kg.

Table 2: HEU Assigned to Major Programs, September 1991, in kg(a)

Major Programs	HEU	U 235	%U 235 (average)
Nuclear Weapons Program	478	418	87.4%(b)
Safari Reactor Fuel Program			
Sent to Safari	83	38	46%
Stored elsewhere	130	60	46%
Subtotal	**213**	**98**	**46%**
Protea (zero power reactor)	5	2.3	46%
Blending	169	111	66%
Total	**865**	**629**	**73%**

(a) The difference between the amount of HEU produced by the Y Plant and the quantity assigned to major programs is 128 kilograms. Most of this material was stored. Small amounts of HEU in this category were used in other programs and about 10 kilograms were classified as lost during processing. South Africa stated in 1991 that the Y Plant produced about 921 kilograms of HEU, which implies that about 55 kilograms of usable or recoverable HEU were not assigned to major programs. The other 70 kilograms of HEU were recovered, identified, or measured after the Y Plant closed.
(b) The HEU assigned to the nuclear weapons program was either about 90 percent or about 80 percent enriched, with most being 90 percent enriched.