FUEL MANUFACTURE IN SOUTH AFRICA: THE ROAD TO CONVERSION

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ABSTRACT

THE SOUTH AFRICAN RESEARCH REACTOR FUEL MANUFACTURING FACILITY (MTR FUEL) WAS ESTABLISHED IN THE 1970'S TO SUPPLY SAFARI-1 WITH FUEL AND CONTROL RODS. LOCAL CAPABILITY WAS DEVELOPED IN PARALLEL WITH THE SA URANIUM ENRICHMENT PROGRAM TO MEET THE VARYING NEEDS OF THE REACTOR. IN JULY 2005 THE SOUTH AFRICAN DEPARTMENT OF MINERAL AND ENERGY AUTHORISED THE TRANSITION OF SAFARI-1 FROM HEU FUEL TO LEU SILICIDE FUEL, WHICH INCLUDES THE CONVERSION OF THE MTR FUEL FACILITY.

PAST EXPERIENCES AND THE STATUS OF THE MTR FUEL FACILITY ARE DISCUSSED. FUTURE PLANS FOR THE LOCAL MANUFACTURE OF LEU FUEL AND PLANNED CO-OPERATION WITH AREVA CERCA, THE FRENCH MANUFACTURER OF RESEARCH REACTOR FUEL ELEMENTS, IS EXPLAINED AND ELABORATED ON.

1. Introduction

The birth of the South African Nuclear industry and subsequent programs has been extensively documented in a wide variety of books, publications and journals. Extensive reporting of the commissioning and operation of SAFARI-1 Research Reactor as well as the various conversion, enrichment, PWR fuel fabrication and other strategic projects have dominated discussions for many years [1] [2].

SAFARI-1 (1st South African Fundamental Atomic Research Installation) a tank-in-pool type light water reactor based on the Oak Ridge Reactor was constructed in the early 1960's to meet the needs of resident research and development scientists and selective isotope production needs. The 6.67MW reactor went critical on 18 March 1965 and was subsequently modified to enable operation at 20MW. The reactor was fuelled with Highly Enriched Uranium (HEU) manufactured either in the USA or UK.

SAFARI-1 was regularly operated at 20MW until 1977, at which stage international restrictions on the supply of fuel elements were enforced by political boycott actions. The reactor schedule was adjusted to an operational level of 5MW to support intermittent R&D programs. These developments spurred on the acceleration towards the establishment of a Fuel Fabrication Facility for the local supply of Fuel and Control Rods.

The chronological graph (Figure 1) explains the utilisation of SAFARI-1 since 1965. The left-hand Y-axis indicates the actual MWh operation of for each 3-month period and the right-hand Y-axis the cumulative MWh of operation since start-up.

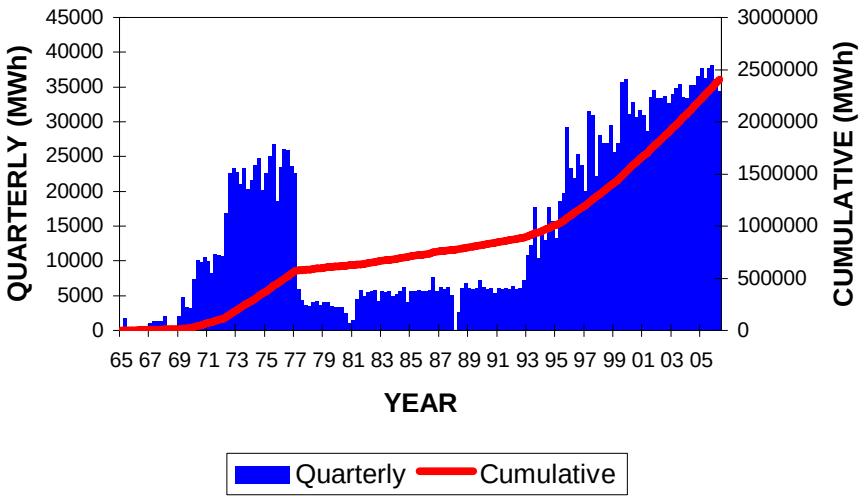

Figure 1: SAFARI-1 Power History (MWh/quarter and Cumulative)

Table1 indicates the HEU Fuel Source and the transition from international to local fuel.

Date	Description of Activity	Utilisation Level (%)	HEU /Fuel Source
1965 (March 18)	First criticality	-	USA
1965 - 1969	Conversion from 6.67 MW to 20 MW and establishment of experimental facilities	< 5%	USA
1970 – 1977	Utilisation of experimental facilities for R&D	~60%	USA/UK
1977 – 1981	Political boycott – fuel sparingly used for R&D	~10%	USA/UK (Inventory)
1981 - 1987	Local fuel manufactured with ~45% enrichment	~15%	SA
1988	Shutdown - plant maintenance and refurbishment	-	-
1989 – 1993	Moderate operation - optimised supplies and R&D	~20%	SA
1993 →→	Democratic Government - lifting of political boycott HEU (45&90%) allocated to target & fuel program Initiation of semi-commercial program	>80%	SA
2005 →→	Continuation of commercial and R&D allocations Initiation of LEU conversion program (~4 years)	>80%	SA

Table 1: SAFARI-1 Chronological Utilisation

2. HISTORICAL DEVELOPMENT – SOUTH AFRICAN FUEL MANUFACTURE

It is clear from Figure 1 that the political climate, the priority of the South African strategic programs and the impact of boycotts related to the supply of nuclear fuel to South Africa significantly affected SAFARI-1 utilisation for the period 1977 to 1993. It was in this period however (late 1970's) that the decision was made to establish local fuel manufacturing capabilities at Pelindaba. A Fuel Element Production Facility (Elprod) was constructed and commissioned in order to manufacture UAlx HEU fuel elements and control rods. The technology applied had been developed and established locally, based on ORR fuel design criteria using initially 45% enriched material and later 90% ^{235}U. The first assemblies (19 flat plates) had a loading of 200g ^{235}U, which was subsequently upgraded to 300g ^{235}U. The first local fuel (45%, 200g) was loaded into SAFARI-1 in 1980/1981 and the first local 90% (200g) HEU elements in 1994. 300g ^{235}U elements were loaded for the first time in the first quarter of 1999.

Of particular significance was the successful development and manufacture of fuel elements of 45% enrichment. As is well known the UAlx system at higher concentrations of U presents particular fabrication difficulties (casting, rolling etc), which were successfully overcome. These developments have made an ongoing contribution to the successful ^{99}Mo production program – target plates to this day are manufactured from 45% enriched material using technology developed in the 1980's!

Figure 2: SAFARI-1 FUEL ELEMENT (19 Fuel Plates)

3. FUEL AND TARGET PLATE MANUFACTURE AT NECSA – CURRENT STATUS

The status of fuel manufacture at Necsa for the past 10–12 years has been consistent and stable in terms of manufacturing quantities with routine manufacture of HEU fuel elements and control rods taking place to meet SAFARI-1 requirements. The MTR Fuel Group consists of a Uranium Chemistry Section (Uchem) primarily tasked with the recovery of HEU and melting and casting UAlx ingots and a Fuel Fabrication Section (Elprod) responsible for fuel plate, target plate, component manufacture and assembly of fuel elements.

The HEU recovery and conversion facility (Uchem), which was incorporated into the MTR Fuel Fabrication Group in the early 1990's has focussed on recovery of HEU from a variety of uraniferous materials remaining after the closure of the strategic programs. Uranium metal is currently recovered from all forms of "scrap material" and processes typically include:

1) **dissolution of solid forms and subsequent manufacture of uranyl nitrate**
2) **liquid-liquid extraction of impurities (TBP process)**
3) **conversion of uranyl nitrate to ADU and UF_4**
4) **calciothermic reduction to U metal**
5) **melting and casting of UAlx for fuel plate meat**

This facility and processes have proven to be an invaluable source for the recovery of enriched uranium for fuel and target plate manufacture.

The Elprod Facility continues to manufacture fuel, control rods and target plates as well as all components required in the manufacture of fuel elements. Fuel Element End Adapter castings with a complex inner profile, which have proved problematic for many years due to casting defects are now manufactured by CNC machining from extruded aluminium alloy. Although fabrication costs are somewhat higher, excess machining capacity and the significant improvement in quality (particularly welding) have made the alternative fabrication method a preferred option.

The MTR Fuel Group has manufactured 722 Fuel Elements and 131 Control Rods to date (about 15800 fuel plates) with no fuel failures directly attributed to fuel quality in SAFARI-1.

Currently about 40 Fuel Elements per annum and 8–9 Control Rods are manufactured. Target plates are manufactured in accordance with NTP Radioisotopes (Pty) Ltd requirements for the supply of ^{99}Mo.

4. THE WINDS OF CHANGE – HEU to LEU

In July 2005 the South African Department of Mineral and Energy affairs authorised SAFARI-1 and the MTR Fuel Plant to convert from HEU to LEU fuel over a period of 3-4 years (i.e. a phased conversion of the core).

Experimental U_3Si_2 (4.8g/cc) work has been underway at MTR Fuel since ~2002 albeit on a development scale and with assistance from Argonne National Laboratories and the French research reactor fuel manufacturer AREVA CERCA.

Typical challenges confronted the development team, which included resolving technical problems associated with arc-melting, communiting and selection of particle size, die design, selection of cladding, rolling schedules, homogeneity, stray particle presence and typical dog-bone formation - a host of technical issues experienced at some stage or other by most manufacturers of silicide fuels of higher density.

Challenges facing the MTR Fuel group in this conversion phase include:

1) **Uninterrupted production (and subsequent phasing out) of HEU fuel elements and control rods in accordance with the SAFARI-1 conversion requirements**
2) **Ongoing production of target plates for ^{99}Mo irradiation.**
3) **Development (including resolving of technical problems) and manufacturing qualification of Silicide Fuel (4.8g/cc).**
4) **Manufacture of 2 LEU Silicide LTA's for irradiation in SAFARI-1 and subsequent limited LTA manufacture utilising the development facility.**
5) **Specification of a Silicide production facility for powder and core manufacture (processes and equipment).**
6) **Design, licensing, construction, cold and hot commissioning of Silicide production facilities (2-3 year project).**

It soon became apparent that Necsa and the MTR Fuel group did not have the resources (manpower) to address the production, technical development and production facility design and other requirements in parallel, and that technical co-operation with an experienced manufacturer would have significant benefits.

The MTR Fuel Group and AREVA CERCA, a long-standing business associate of NECSA, held preliminary discussions in the middle of 2005 where the concept of potential technical co-operation was discussed and finally agreed upon.

5. CERCA EXPERIENCE IN SILICIDE FUEL MANUFACTURING AND MTR CONVERSION

CERCA, a subsidiary of AREVA, has been in charge of manufacturing and supplying research and test reactor fuel assemblies for more than forty years and is the world leader in its field. CERCA supply covers a large range of products, in terms of geometries (flat or rolled plates, tubular or ring-shaped elements) as well as enrichments (HEU, MEU, LEU), and fully satisfies the technical and scientific needs of customers demanding quality and security.

Since 1960, CERCA has manufactured over 300 000 fuel plates, about 20 000 fuel elements of 70 designs, delivered to 40 research reactors in 20 countries.

Thanks to this broad supply, CERCA has gained a high quality experience feedback. This is employed to the benefit of reactor operators by providing them with high performance fuels.
One of the ways of development CERCA has been working on for more than 20 years concerns improvement of low-enrichment fuel performance levels by increasing uranium-235 loading per plate without changes in external geometry. This has been achieved with silicide U_3Si_2 fuel (standard and control fuel assemblies) that CERCA manufactures on an industrial scale and routinely delivers worldwide.

By mid-2006, CERCA has manufactured 2700 U_3Si_2 fuel assemblies (about 55 000 plates), for customers distributed in Australia, France, Germany, Greece, Netherlands, Japan, Canada, South Africa, Sweden, Switzerland, Taiwan and Turkey.

CERCA manufacturing plant, located in Romans in the south of France, has a global manufacturing capacity of 20 000 plates. The annual production is around 10 000 plates, 50% of which are U_3Si_2 fuel plates.

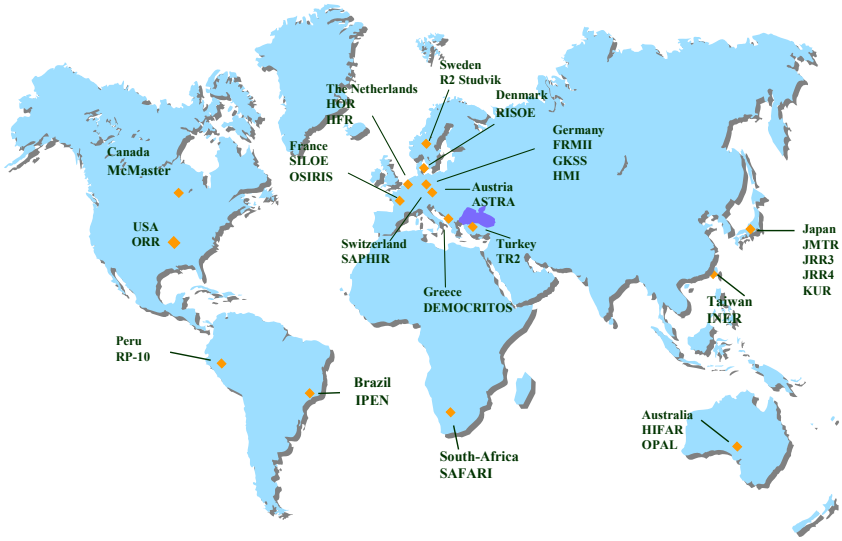

Figure 3: CERCA U_3Si_2 customers

Since the first fuel test assemblies, delivered to the Oak Ridge Research Reactor in 1983, considerable progress was accomplished in the production standards. From that time new production equipment and processes have been implemented to fulfill the specific silicide fuel requirements.

For example:

- **A new arc melting furnace has been supplied**
- **A dedicated powder manufacturing line has been installed**
- **New core pressing tools have been designed**
- **New rolling sequences have been developed**
- **Numerical X-ray machine has been developed to assist operators for fuel core length adjustment**

CERCA has also implemented a quality system for inspection of the fuel plates at each step of the manufacturing:

- **UT inspection: special UT inspection equipment enables detection of delamination within the meat that cannot be detected with a blister test**
- **Radiographic inspection and film inspection: controlling of the stray particles by microscope on X-rays films and also accurate dimensional inspection of the cores**
- **Homogeneity inspection: numerical X ray machine and software systems for obtaining a map of uranium density in the plates and knowing the exact density value at each square centimeter**
- **Dimension check and surface defect check on finished plates**
- **Final inspection including contamination check**

In addition to the manufacturing experience, there have been many in-reactor tests and examinations, from 1982 to 1998, involving U_3Si, U_3Si_2, with a Uranium density between 2 and 6 g/cm^3. This extensive program of test and development covered various design parameters, such as meat chemical composition and densities. Several production parameters were also varied, keeping the industrial conditions. Industrial conditions, as opposed to laboratory conditions, refer to manufacturing in the same workshop, with the same people, using the same equipment, work instructions, Quality system, etc, as for the standard production.

At each step of the development, CERCA has been driven by the reliability of the solution proposed and has endeavoured to carry out all developments with standard manufacturing tools, on full size plates and with a significant number of elements. This has allowed CERCA to overcome the all too well-known gap between R&D with few test elements and standard production in large series. As a result, the prototype fuel assembly loaded in HFR-PETTEN in 2003 has exceeded 75% of burn up and is exhibiting an excellent behavior.

With continuous contacts with the research reactor community around the world and thanks to its large manufacturing experience, CERCA knows very well what is important from a safety standpoint, as far as fuel manufacturing is concerned, and can address individual customer needs and any special quality requirements in consistency with safety authorities' demands.

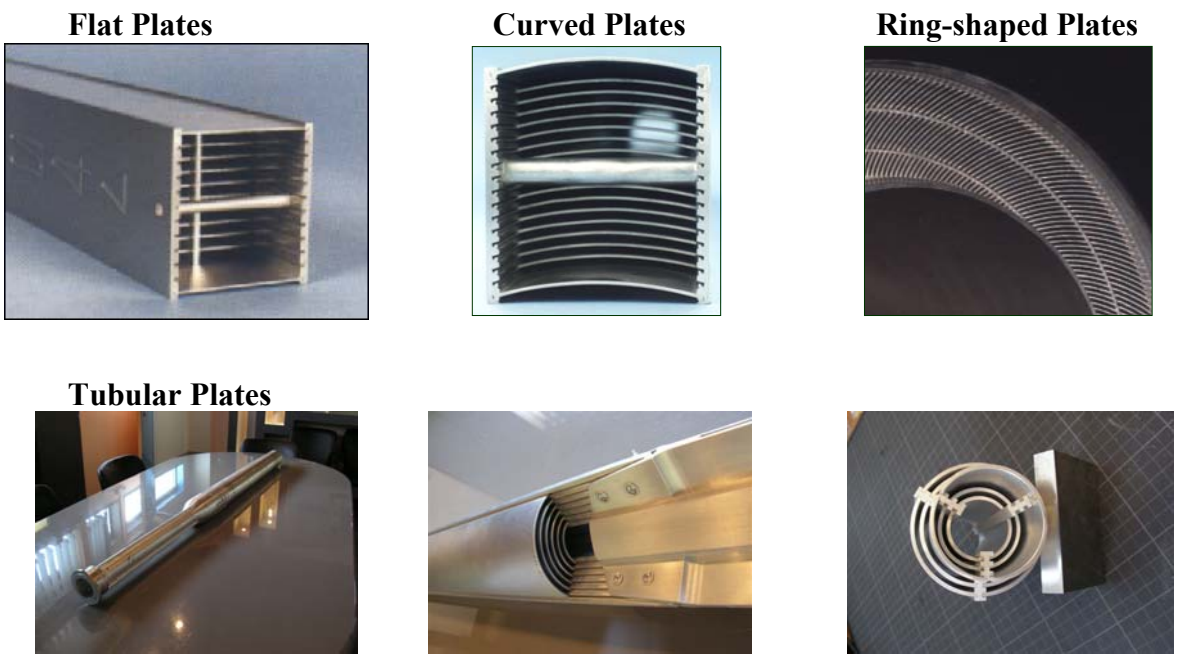

Figure 4: Main fuel designs manufactured by CERCA

CERCA Experience in Research Reactor Conversion

CERCA has been involved for more than fifteen years in international cooperation for U_3Si_2 fuel assembly supply and reactor conversion. It has collaborated several times for reactor conversion process, for MTR and TRIGA reactors, in countries such as Japan, Belgium, Germany, the Netherlands, the USA. Presently, CERCA is collaborating with the USA regarding the conversion of the Washington State University Triga reactor and RPI MTR reactor in Portugal.

6. PLANNED CO-OPERATION BETWEEN NECSA AND CERCA: A LONG TERM RELATIONSHIP

NECSA and CERCA commenced a formal partnership from early 2004 by means of a Memorandum of Understanding and have been working together in different fields such as the supply of two LTA's for SAFARI-1, fuel plate supply, uranium delivery, fuel plate evaluation and preliminary evaluation of a concept silicide fuel plant design (powder and core manufacture).

To support the MTR manufacturing conversion process, the purpose is now to bring to NECSA technical cooperation and expertise for establishing a qualified production line for LEU fuel and mastering the new manufacturing processes.

Various proposals were tabled and a point is being reached where two phases of technical assistance and co-operation are in the process of being finalised.

6. 1 Short-term technical assistance initiative:

The first step of this collaboration will concern the manufacturing performed on a laboratory scale. CERCA will evaluate the current MTR Fuel processes, propose improvements and validate the LTAs manufactured by NECSA through verification of compliance to the Necsa technical specification. This assistance is planned for the beginning of 2007, at the Pelindaba manufacturing facility.

6.2 Longer term cooperation agreement:

The second step will consist in assistance for the manufacturing on a production scale. CERCA will perform:

- **Evaluation of NECSA existing production processes and equipment**
- **Training of NECSA staff on the different steps of manufacturing of silicide fuel and inspection processes. This training will be performed at CERCA manufacturing plant in Romans-France.**
- **Technical assistance during starting of the new equipment at the MTR Fuel plant at Pelindaba**
- **Validation of the first production run manufactured by NECSA**

This assistance is scheduled to take place during 2007 and 2008.

7. CONCLUSION

South Africa has committed itself to the conversion of the SAFARI-1 research reactor and the associated fuel and control rod manufacturing from HEU to LEU utilisation. Significant in-house progress has been made regarding development of the applicable manufacturing techniques, together with selective assistance from both the Argonne National Laboratories and the research reactor fuel manufacturer, AREVA CERCA. Final stages of development to achieve qualified licensed fuel initially on an experimental scale (Lead Test Assemblies) followed by a full production scale facility are being addressed together with CERCA.

This cooperation will strengthen the long-lasting relationship between NECSA and CERCA and develop mutual benefit for the two companies. Thanks to this assistance and experience provision, NECSA will be able to manufacture the LEU fuel elements for the SAFARI-1 reactor and gain additional skills and competences in the manufacturing field. On its side, CERCA will gain new experience in research reactor conversion. Moreover, this operation will contribute to meeting the international requirement on global reduction initiatives.

8. REFERENCES

[1] AR Newby Fraser, "Chain Reaction: 20 Years of Nuclear Research and Development in South Africa", ISBN 086960 6964, 1979
[2] CSB Piani, South Africa and the SAFARI–1 Scenario: On the Road to Conversion – From HEU to LEU, RERTR 2005