RERTR 2010 — 32nd INTERNATIONAL MEETING ON
REDUCED ENRICHMENT FOR RESEARCH AND TEST REACTORS

October 10-14, 2010
SANA Lisboa Hotel
Lisbon, Portugal

STATUS OF CONVERSION OF THE SOUTH AFRICAN SAFARI-1 REACTOR AND ^{99}MO PRODUCTION PROCESS TO LOW ENRICHED URANIUM

G. Ball
Technology Division
NTP Radioisotopes (Pty) Ltd
PO Box 582, Pretoria, 0001 – South Africa

ABSTRACT

The SAFARI-1 research reactor and NTP ^{99}Mo production facilities at Pelindaba continue to produce and distribute significant quantities of ^{99}Mo for the world nuclear medicine market. Over a number of years a significant effort has been made, both in the conversion of the reactor fuel and ^{99}Mo targets, from HEU to LEU.

The reactor became operational in March 1965 and has consistently recorded an impeccable safety record with a high level of utilization. The reactor was originally operated with HEU UAl_x alloy fuel until conversion to LEU U_3Si_2 dispersion fuel which was initiated in February 2006 with the irradiation testing of lead test assemblies. As from August 2008, increasing numbers of LEU fuel assemblies were loaded into the core until completing conversion in June 2009.

NTP has been producing ^{99}Mo commercially using HEU since 1994 using a locally developed method. Work on converting the ^{99}Mo production process to LEU began in all earnest in 2007 and various successes have been achieved recently.

This paper briefly describes the history of conversion of the SAFARI-1 fuel to LEU and the successful completion thereof as well as the progress being made with the conversion of the ^{99}Mo production process.

1. Introduction

The SAFARI-1 research reactor is owned by the South African Nuclear Energy Corporation (Necsa). The name SAFARI is an acronym for the South African Fundamental Reactor Installation. It was commissioned in 1965 and has a designed thermal power of 20 MW. Since commissioning, it has operated with an exemplary safety record. Commercial and research programs at the reactor are supported with an extensive infrastructure, ranging from theoretical reactor physics, radiochemistry and radio-analytical groups, a fuel and target fabrication plant, hot cell facilities for the production of medical and industrial isotopes, a pipe storage facility for the interim dry storage of spent fuel and a disposal site for low and intermediate radioactive waste.

NTP Radioisotopes (Pty) Ltd, a limited liability company, is a wholly owned subsidiary company of Necsa. Its primary focus is the production and distribution of various radiochemicals to both the medical and industrial sectors. NTP also produces various radiopharmaceuticals such as its locally developed NovaTec-P ^{99m}Tc generator, ^{18}F based PET products and ^{131}I capsules and solutions.

Necsa and NTP have supported the principles of the Reduced Enrichment for Research and Test Reactor (RERTR) Programme for many years and have actively worked towards converting both SAFARI-1 to LEU fuel and the ^{99}Mo production process to LEU targets within the technical and commercial constraints facing it. It should also be noted that despite the recent international crises with regards to ^{99}Mo production and supply, NTP continued to develop and industrialize its LEU based ^{99}Mo production process while ensuring the development programme did not influence routine ^{99}Mo supply.

2. Facility Description

The reactor which is similar in design to the Oak Ridge Reactor (ORR), is light water cooled and moderated with an 8 x 9 core lattice which currently contains 26 fuel assemblies (active height 600 mm) and 6 control assemblies, as depicted in Figure 1. The remaining lattice positions are either aluminium or beryllium reflector elements. The fuel assemblies consist of 19 flat plates each, originally constructed from uranium-aluminium alloy but more recently from U_3Si_2 powder dispersed in an aluminium matrix and clad with aluminium. The reactor vessel is cylindrical in shape, with one flattened side which forms the northern wall of the rectangular core box, thereby providing an easily accessible pool side facility, directly adjacent to fuel assemblies and therefore relatively high neutron fluxes.

SAFARI-1 has operated on 5 different fuel types during its history. It was originally fuelled with imported 90 wt% enriched uranium (HEU) aluminium alloy fuel but was converted to locally fabricated (and enriched) 45 wt% enriched uranium (MEU) aluminium fuel in the early 1980's. The reactor was converted back to HEU during the 1990's and the density of uranium in the fuel was increased. In the mid to late 2000's it began its transition to LEU uranium silicide fuel.

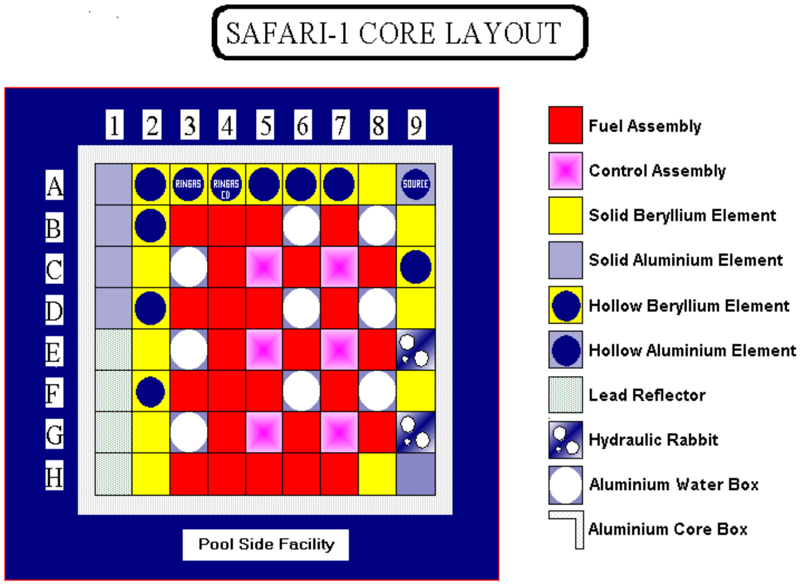

Figure 1. A schematic representation of the SAFARI-1 core layout

NTP's radiochemical production facility consists of 3 large concrete shielded hot cells and 22 smaller lead shielded hot cells. The facilities were originally used for the post irradiation examination of power reactor fuel but were substantially modified in the early 1990's to accommodate ^{99}Mo and other radiochemical production.

The ^{99}Mo production process was developed in the late 1980's and early 1990's and the first ^{99}Mo commercially exported in 1994. The plant was upgraded and scaled-up further based on the operational experience gained from the early years of operation.

Currently, the SAFARI-1 reactor is operated for approximately 303 days per year resulting in a high availability while the radiochemical production facility is operated for 51 out of every 52 weeks. This high level of operability is due to extensive maintenance programmes and aging management projects.

3. SAFARI-1 Fuel Conversion

The study into the feasibility of converting SAFARI-1 to LEU was conducted in 2 parts. Firstly, a technical feasibility study was conducted jointly by Necsa and Argonne National Laboratory (ANL) staff during 1994 and 2001. Various U_3Si_2 and UMo fuel types (see Table 1) with various designs were considered and detailed results published during various RERTR meetings and ANL reports [1] [2] [3].

Table 1. Fuel types

Name	Meat	^{235}U Mass (g)	# plates	Assemblies used per annum
HEU300-19 (Base case)	U-Al	300	19	39
LEU340-19	U_3Si_2	340	19	35
LEU320-19	U_3Si_2	320	19	39
LEU340-23	U_3Si_2	340	23	38
LEU320-19Mo	U7%Mo	320	19	41

Table 2. Thermal flux percentage differences relative to base case

Irradiation facility	LEU340-19	LEU320-19	LEU340-23	LEU320-19Mo
In-core thimbles	-5.1	-3.7	-3.0	-5.0
In-core high flux	-6.1	-4.3	-5.8	-4.7
Hydraulic	-4.0	-2.9	-1.3	-4.7
Pool side	-8.5	-8.5	-7.6	-9.3

The results over all fuel types indicate a thermal flux decrease ranging between 3% and 9% in the irradiation positions (see Table 2) with the UMo fuels tending to result in slightly larger thermal flux decreases. The technical feasibility study further showed that all of the safety criteria of SAFARI-1 would be met with the LEU fuel.

The results of the technical study were used as input to an economic feasibility study which was conducted during 1995 and repeated in 2001. A thorough economic analysis was performed taking into account the impact of LEU fuel on the operational costs of the reactor (primarily fuel costs) as well as the impact of the flux changes in the irradiation positions on the production of radioisotopes. Changes to routine operational costs and to production capacity as well as once-off costs associated with conversion were included in the study.

Although all options considered indicated an overall net cost increase as well as a decrease in turnover due to reductions in neutron fluxes in irradiation positions, the economic analysis was helpful in the selection of a suitable option taking the economic impact into account.

During 1995, the decision was taken not to convert due to the commercial programme being in its infancy stage and the financial risks of conversion were considered too great a risk for the business. However, in 2001, based on the growth and stable nature of the business, the decision to convert the fuel to LEU was taken.

Table 3 below summarizes the timeline of the conversion of SAFARI-1 to LEU fuel. As can be seen, the conversion was completed in June 2009. The measured fluxes and reactor performance are in accordance with the theoretically calculated data. The reactor has operated on LEU silicide fuel for the past 15 months without incident.

Table 3. Timeline of Events for SAFARI-1 Fuel Conversion

Year	Event
1994	Technical Feasibility Study performed (jointly with ANL)
1995	Economic Feasibility Study performed at 1995 conditions
2001	Technical and Economic Feasibility Study redone at 2001 conditions
2005	Government approves conversion of SAFARI-1
2006	First test irradiations of LEU fuel commenced
August 2008	Nuclear Regulator approved conversion
September 2008	Conversion commenced
June 2009	Conversion completed

4. Conversion of ^{99}Mo Production Process

NTP has been producing ^{99}Mo from 45% enriched uranium for over 16 years and consequently has a wealth of experience of its process and plant. It was this experience base that was used to expedite the project to convert its production process to LEU. The conversion strategy was divided into two distinct phases. The first being a target which results in minimum changes to the current process while the second phase being a significantly different target (high density) and process but with significant benefits.

For the first phase NTP clearly listed its main requirements for the selection of a suitable target as follows:

- Minimum changes to target, irradiation, handling and chemical processing,
- Production capacity to be maintained or increased,
- No interruption to current routine production.

The target technology selected for phase 1 was a uranium-aluminium dispersion target. Table 4 below shows the current status of the timeline for phase 1.

Table 4. Phase 1 Timeline of events for ^{99}Mo production Process conversion

Year	Event
2007	Theoretical Feasibility Study Performed
2008	Cold and Depleted Uranium Experiments Performed
October 2009	Nuclear Regulator Approval Received for Hot Test Phase Hot Test Phase Commenced
March/April 2010	Process Validation Runs Performed
June 2010	Submission to Nuclear Regulator for Routine LEU ^{99}Mo Production Submission to Medical Regulators Commenced
July 2010	Customer Tests and Validation Runs Commenced
September 2010	Nuclear Regulator Approval Received for Routine LEU ^{99}Mo Production

The process development and validation runs have been completed and the ^{99m}Tc generator manufacturers are currently busy with their validation runs. Figure 2 below gives the batch sizes of the ^{99}Mo runs performed to date calibrated to end-of-irradiation.

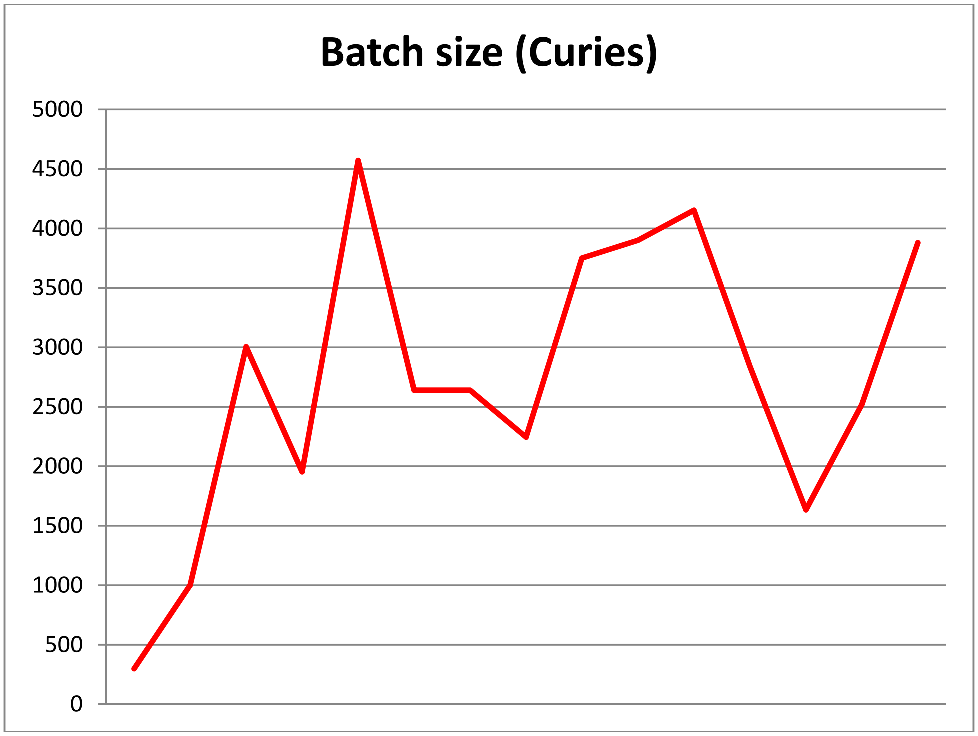

Figure 2. Batch sizes of runs performed to date

The production yields relative to those obtained for the 45% enriched targets are given in Figure 3. This indicates that the process changes introduced have substantially improved the process efficiency and are now equivalent to those of the 45% enriched targets. It must, however, be noted that the batch sizes have decreased by approximately 10% due to the ^{235}U loading in the LEU targets being lower as a result of total uranium density restrictions in the dispersed target.

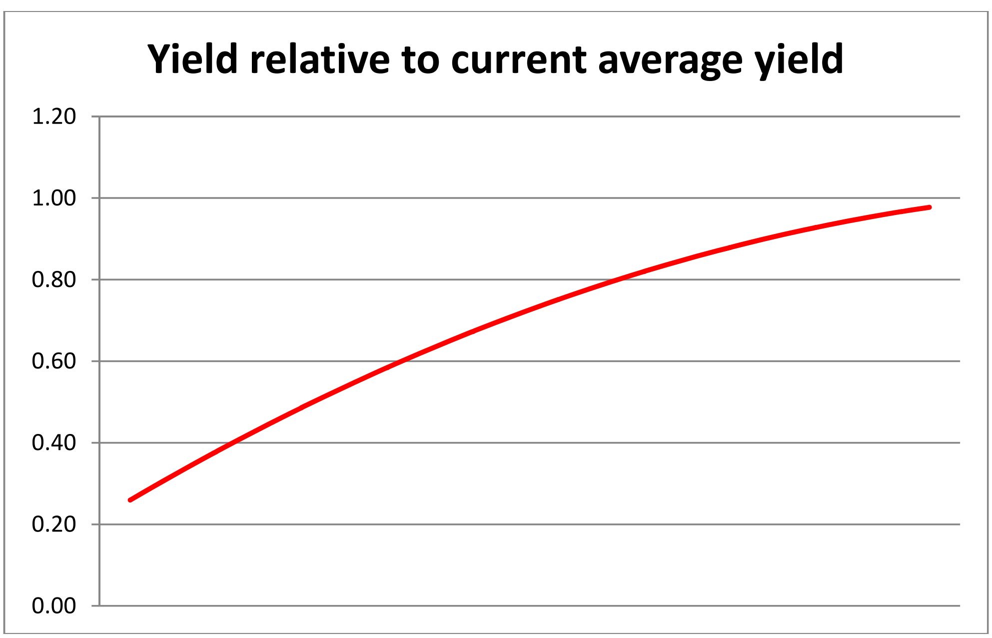

Figure 3. Production yields relative to current process

As expected, from a safety perspective there were no issues encountered regarding the LEU targets both from the reactor irradiation side as well as from the processing side. The measured data confirmed the theoretical calculations.

The ^{99m}Tc eluted from NTP's NovaTec-P generators fully conformed to United States, British and European pharmacopeias and no difference could be seen between cold kits labeled with HEU or LEU origin ^{99}Mo. In some of the runs, however, tungsten was detected in the ^{99}Mo product. NTP is working together with the target manufacturers to address this.

As far as the waste is concerned, the largest problem was the significant increase in mass of uranium. This caused both filtration problems in the process and waste storage capacity challenges. These are currently being addressed.

From a production capacity viewpoint, the current manufacturing technology available for the uranium-aluminium dispersion target has resulted in a 10% lower ^{235}U mass being loaded into the targets. This naturally results in the current production capacity being reduced by 10%.

5. Conclusions

After many years of work, the SAFARI-1 reactor has been successfully converted to LEU silicide fuel and continues to operate reliably and safely with this fuel. Building on this success, the first phase of the conversion of the ^{99}Mo target and process has proceeded extremely rapidly albeit with some challenges along the way.

Necsa and NTP are firmly of the opinion that true conversion implies that both the reactors used to irradiate the targets as well as the targets themselves need to be LEU before it can be claimed that ^{99}Mo is produced using LEU. This is also clearly evidenced by the steps taken in South Africa over the past years.

There are, however, a number of disadvantages to conversion. The first being due to fuel and target cost increases. The current LEU silicide fuel and dispersion targets have to be imported due to Necsa not having the technology to produce it internally as was done with the uranium-alloy fuel and targets.

The second disadvantage is due to ^{99}Mo production volume decreases. This is for two reasons; namely due to conversion of the SAFARI-1 fuel to LEU the thermal flux decreases in target irradiation positions resulting in lower ^{99}Mo production and also due to the maximum amount of ^{235}U which can be loaded into the LEU dispersion target being less than the current HEU targets

The third disadvantage is due to the significant increase in the mass of uranium which has to be handled and stored.

Nevertheless, Necsa and NTP remain committed to completing the conversion of its ^{99}Mo process and switching over to LEU production but need to caution that the net effect is an increase in production costs and a decrease in production capacity.

6. References

[1] G. Ball, R. Pond, N. Hanan and J. Matos, "Neutronic Study on Conversion of SAFARI-1 to LEU Silicide Fuel", Proceedings of the XVII International Meeting on Reduced Enrichment for Research and Test Reactors, Williamsburg,Virginia, USA, 18-23 September 1994.

[2] G. Ball, R. Pond, N. Hanan and J. Matos , "Technical Feasibility Study of Converting SAFARI-1 to LEU Silicide Fuel", ANL/RERTR/TM-21, May 1995.

[3] G R. Pond, N. Hanan, J. Matos and G. Ball, "A Neutronic Feasibility Study for LEU Conversion of the SAFARI-1 Reactor", Proceedings of the XXIII International Meeting on Reduced Enrichment for Research and Test Reactors, Las Vegas, Nevada, USA, 1-6 October 2000.

[4] G. Ball and F. Malherbe, "Techno-Economic Study on Conversion of SAFARI-1 to LEU Silicide Fuel", Proceedings of the XVIII International Meeting on Reduced Enrichment for Research and Test Reactors, Paris, France, 18-21 September 1995.

[5] W. Stumpf, A. Vermaak and G. Ball, "Key Considerations in the Conversion to LEU of a Mo-99 Comercially Producing Reactor: SAFARI-1 of South Africa", Proceedings of the XXIII International Meeting on Reduced Enrichment for Research and Test Reactors, Las Vegas, Nevada, USA, 1-6 October 2000.