The role of SAFARI-1 in industry and academia

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The Role of SAFARI-1 in Industry and Academia

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Abstract

The South African Nuclear Energy Corporation (NECSA) owns and operates the SAFARI-1 20MW Research Reactor. In fulfilling its mandate from government to apply radiation technology for scientific purposes, NECSA is constantly exploring opportunities to employ the neutrons from its beam line facilities to benefit both academia and industry in research and technological development. This goal is approached through joint ventures with industry and academia. This paper outlines the facilities available at SAFARI-1 and their application to various fields.

1. Introduction

SAFARI-1, the research reactor of NECSA, plays a prominent role in the delivery of products and services to various sectors of international and local industries. The utilisation of SAFARI-1 can be divided broadly into two groups; commercial and institutional. In the first case in-core irradiation positions and pool-side facilities are used for income generation through sales to the South African and international markets. Institutional activities are defined as services to, and in collaboration with, the higher education sector and other government funded institutions, nationally and internationally.

Through the application of extensive experience in nuclear sciences, chemistry and physics, internationally competitive technologies have been developed. These include the production of medical radio-isotopes and the neutron transmutation doping of silicon. Today, SAFARI-1 is one of the world leaders in these fields.

NECSA is constantly exploring opportunities to utilise SAFARI-1 to benefit the local industry in research and technology development. Unique facilities have been developed on the external beam lines of SAFARI-1 to support local industries with high technology non-destructive analysis methods of materials and components. Neutron radiography and various neutron diffraction based techniques serve as examples.

The institutional value of SAFARI-1 resides in non-commercially exploitable positions of the in-core and pool-side facilities, pneumatic and hydraulic facilities, and in the six horizontal radial beam lines that can deliver neutron beams external to the reactor pool. Presently three of the beam lines are equipped for neutron diffraction, neutron radiography and prompt-gamma neutron activation analysis applications. These facilities are continuously adapted and upgraded to make the areas of forefront research topics more available to the South African research community for example, adaptation of one of the beam lines for small angle neutron scattering. Additional beam lines can be developed to support alternative applications.

SAFARI-1 furthermore plays an integral role in the training of scientists and engineers up to post-graduate level and offers very attractive research opportunities for the scientific community in South Africa.

2. Description of facilities

SAFARI-1 is a light-water cooled and moderated research reactor that produces neutrons for commercial applications, as well as in support of industrial technology development and research [1]. A schematic representation of the reactor lay-out is given in Fig. 1 where the irradiation regions are marked as A, B and C.

2.1. *The reactor poolside facility*

Bulk samples can be irradiated in relatively high neutron fluxes ($\sim 10^{13}$ n $\cdot$ cm^{-2} s^{-1}) close to the fuel assembly outside the core vessel (region A) with fast neutrons, thermal neutrons and gamma rays. This facility is primarily used for the neutron transmutation doping of silicon ingots used in the semiconductor industry.

2.2. *Incore irradiation positions*

Positions exist between the fuel elements (region B) to provide the highest fluxes ($\sim 10^{14}$ n $\cdot$ cm^{-2} s^{-1}). Five positions are dedicated to the irradiation of enriched uranium target plates for the production of the fission product ^{99}Mo, used in the medical industry. The possibility to perform materials testing relevant to the latest Pebble Bed Modular Reactor program of ESKOM is currently being explored.

2.3. *Hydraulic and pneumatic facilities*

The hydraulic facilities allow access to the reactor core (region B) for short irradiations, typically of samples for neutron activation analyses (NAA). Irradiations are done with fast neutrons or the total neutron energy spectrum. The system is linked with an analytical laboratory with computer controlled sample irradiation and analyses. The pneumatic facilities are mainly used for accurately controlled, short irradiations on small samples as well as for test purposes.

2.4. *Beam line facilities*

These facilities (region C) exploit the properties of thermal neutrons to analyse various properties and characteristics of condensed matter and engineering components.

2.4.1. *Neutron radiography.* Neutron radiography (NRAD) employs the elementally selective attenuation of thermal neutrons in matter to image the interior of non-transparent

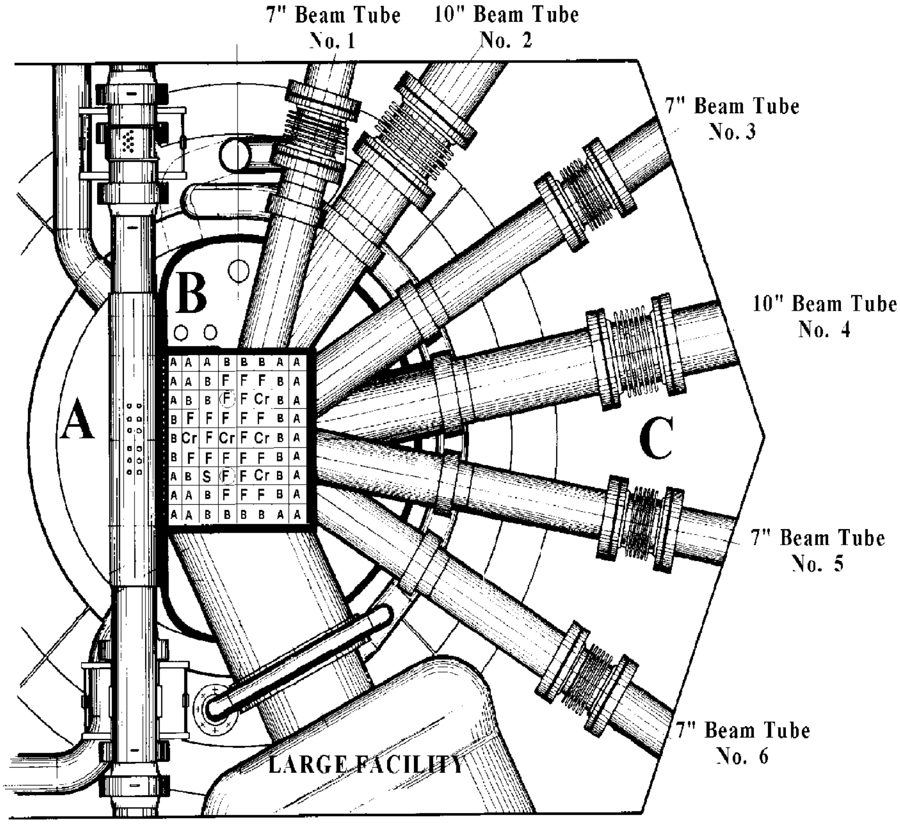

Fig. 1. Layout of SAFARI-1. Position A refers to the poolside facility, B the incore position and C the radial beam lines.

materials and components [2]. A full description of the facility is available [1]. The large attenuation coefficient of hydrogen is especially invaluable in the visualisation of moisture in, for example, concrete and mineral ores. This, coupled with the superior penetrability of neutrons through matter, enables investigation of large structures and components. The current applications of NRAD are focussed on the investigation of moisture in concrete, the detection of aluminium corrosion products, evaluation of components containing explosives, and petrophysical and mineralogical investigations.

2.4.2. *Neutron diffraction.* Neutron diffraction (NDIFF) is an analysis method in which the microstructures of crystalline materials are investigated to provide information on various material properties and phenomena [3]. It exploits the unique properties of thermal neutrons, i.e. uncharged and an intrinsic spin, and their superior penetration capabilities into most materials enabling the non-destructive examination of the interior of materials and components. The identified expertise areas of NDIFF are: residual strain measurements, powder and single crystal diffraction analyses, and studies of magnetic systems.

2.4.3. *Prompt gamma neutron activation analysis.* The prompt gamma-ray emissions, following neutron capture in materials, provide an accurate method for the identification of elemental, and isotopic, content of bulk samples. Sensitivities are typically in the parts per million range. The technique is particularly sensitive to H, B, Cd, Gd and Sm in materials. A potential field of application is in the fingerprinting of geological minerals.

3. Industrial and commercial viability

The utilisation of the reactor is depicted as a continuum consisting of a balance between direct and indirect value addition (Fig. 2). On one side of the scale are activities with a pure commercial motive such as target irradiation for medical isotope production, for which an irradiation fee is charged, i.e. direct value addition. In the middle range are activities such as sample irradiations for neutron activation analysis and non-destructive examination of materials for industrial clients. Here value addition is less direct, i.e. in the form of unique information, which gives the client insight into their specific problems. These services are used in the mining, manufacturing and other industries. On the other extreme is training of personnel and students, which adds indirect value to the South African economy in the form of highly skilled human resources.

4. Products and services

The main areas upon which the commercial utilisation of SAFARI-1 is focussed, are (in order of commercial significance):

- Isotope Production and Irradiation Services.
- Neutron Transmutation Doping (NTD) of silicon.
- Beam lines (NRAD, NDIFF, PGNAA).

Although the technology in each area is established, continuous efforts to improve efficiency and reliability are undertaken through tracking and modelling of the physical processes. The procedures adopted with product development and process improvements are elaborated in the following sections.

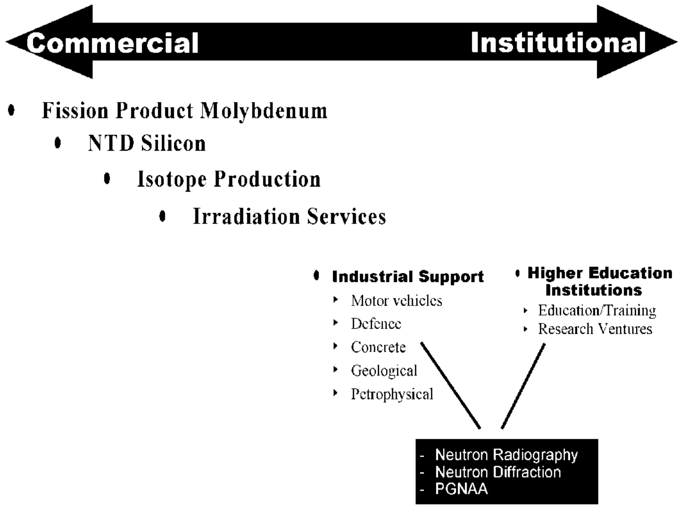

Fig. 2. Industrial and Commercial Viability of SAFARI-1.

4.1. *Isotope production and irradiation services*

These services include the production of radio-chemicals and/or radio-pharmaceuticals. Typically the production process would involve the irradiation of a target material in SAFARI-1, followed by chemical extraction/processing in a modern Hot Cell Complex. The choice of the irradiation positions, irradiation parameters and the design of target material holders are based on neutronic and experimental analysis, to identify the most suitable position and procedure, to ensure maximized production. To ensure the safe operation of the reactor even the rate at which target material may be moved into/out-of the core has to be determined, so as not to adversely affect reactor operation. Substantial experience in material science is applied to the development of construction materials to ensure compatibility with the product formed. An example is iodine radio-isotope production which is highly corrosive.

The radio-isotopes which are produced in SAFARI-1 and their applications are summarised in Table I.

Irradiations requiring no, or very little, post irradiation processing are defined as Irradiation Services. This includes the irradiation of targets for the NECSA's Isotope Production Centre as well as international isotope producers and changing the colour of gemstones. The colour of gemstones can be changed by irradiation with either gammas, electrons, neutrons or a combination thereof [4]. An experimental program, backed by neutronic calculations, has been done to specifically investigate topaz by performing the following:

(a) Evaluate the required neutronic conditions in the irradiation volume, to generate the desired colouration with fast neutrons and gamma rays,
(b) Limit the activation level of the topaz stones (mainly due to thermal neutron capture) to ensure shorter turn around times,
(c) Determine the effect of irradiation temperature and environment on the colouration process through light absorption measurements in the visible spectrum.

Although topaz is coloured world wide, the exact process is still not completely understood and thus poses a huge research potential.

Table I. *Industrial and Medical isotopes produced in SAFARI-1 and their applications.*

Industrial Isotopes		Medical Isotopes	
Isotope	Use	Isotope	Use
^{192}Ir	Radiography	^{153}Sm	Pain Palliation
^{140}La	Fluid transport	^{131}I	Diagnosis and thyroid therapy
^{90}Y	Thickness gauging	^{198}Au	Brachytherapy
^{32}P	Labelling	^{192}Ir	Brachytherapy
^{35}S	Labelling	^{99}Mo	^{99m}Tc generators

4.2. *Neutron transmutation doping of silicon*

The Neutron Transmutation Doping (NTD) process is based on the transmutation of ^{30}Si atoms, by the capture of thermal neutrons, into ^{31}Si, which decays by the emission of beta particles to ^{31}P [5]. A uniform neutron dose distribution over the silicon ingot ensures a homogeneous distribution of phosphorous atoms throughout the crystal, which is more efficient than conventional chemical doping. As a result, NTD silicon is used extensively for the manufacture of high quality semi- conductor devices [6,7].

A theoretical model, based on neutron transport theory methods, predicts the neutron fluxes as a function of neutron energy in the poolside region. Applicable neutron cross-section libraries were prepared to calculate the relevant cross-sections for the activation foils and silicon used during the development and calibration phases. A series of experiments were designed to obtain a comprehensive set of experimental data [8] which served to characterise the irradiation region neutronically, from which an irradiation position was identified for the installation of the first facility in 1992. Due to market changes it was decided in 1995 to upgrade the facility to accommodate silicon ingots with diameters up to 150 mm and lengths of 600 mm. At the same time, an independent second system was installed to substantially increase capacity. Neutronic calculations, backed up with irradiation flux foil experiments were done to (a) optimise the two irradiation positions and (b) to ensure that the two systems did not affect each other during irradiations.

Since commissioning, in June 1996, the production capacity has steadily grown to about 14 tonnes per year. Defect annealing and subsequent electrical characterisation are done by the client. These results are continually used to adjust the irradiation conditions to ensure that the requested resistivities are accurately reached. Figure 3 depicts the accumulated target resistivity accuracies over the production period of the year 2000. Typical axial and radial resistivity profiles are less than 5%, which adhere to the client requirements.

4.3. *Industrial support at the beam lines*

The collaboration and involvement of the beam line facilities at SAFARI-1 with respect to various industries and, where applicable, via tertiary institutions can be summarized as follows:

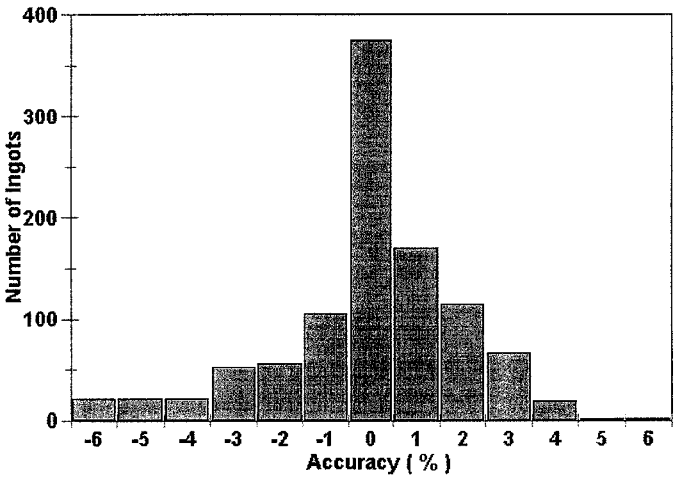

Fig. 3. Accuracies achieved with silicon irradiations

4.3.1. *Aircraft industry.* Aluminium components and structures of aircraft are susceptible to various types of corrosion and fatigue due to aging, frequent changes of environment and moisture. NRAD provides a very sensitive and informative method for the detection of corrosion based on the attenuation characteristics of the hydrogen present in the corrosion products. Blockages in, for example, fuel lines can easily be detected due to the ease of penetration through enveloping structural materials. Components subjected to cyclic loading, such as the landing gear, can fail under processes such as fatigue. NDIFF is applied to the non destructive investigation of the strain state in critical components of air frame and landing gear to assist in remaining lifetime assessments.

4.3.2. *Motor vehicle industry.* The motor vehicle industry, with all its peripheral industries, benefits from the services offered at the beam lines in terms of materials investigations, fault finding and QA inspections. Valuable insight can also be gained with product and/or technology development. NRAD has been applied to solve an air conditioner malfunctioning unit problem without dismantling the component. Controversy with respect to the cause of leaf spring breakages in the suspension of light delivery vehicles was mediated through NDIFF results, where the strain dependences related to specific production processes could be identified.

4.3.3. *Defence industry.* By exploiting the penetrating and discriminatory attenuation nature of neutrons, NRAD was identified as being suitably applicable to QA evaluation of products in the defence industries. Examples are the evaluation of gun powder filling in cartridges and discontinuities in pyrotechnic cords. NDIFF strain investigations are also making valuable contributions in the development of beneficial materials conditioning processes to enhance the fatigue lifetimes of components. Indispens-

Table II. *Format of the institutional projects and collaboration.*

Focus Area	Description of interaction	Format	Institution
Crystallography	Establishment of a national crystallography facility between NECSA, NRF and the crystallography community. Single crystal neutron diffraction supplements the extensive X-ray facilities in providing additional information on the localisation of hydrogen in electron density modelling.	Research Post-graduate projects	University of Pretoria University of the Witwatersrand
Magnetic systems	Studies of magnetic phenomena in Cr alloy systems and heavy-fermion materials to complement indirect methods such as ultrasonics, resistivity, thermal expansion, etc.	Research	University of the Witwatersrand Rand Afrikaans University
Residual strain	Investigations of residual strain fields in engineering materials with neutron diffraction benchmarked against destructive methods and theoretical modelling with finite-element methods.	Post-graduate projects	University of Pretoria
Practicals	Hands-on participation with projects at the beam line facilities to become acquainted with the laboratory environment.	Under and post-graduate students	VISTA University Medical University of SA University of North West
Powder diffraction	Investigation of chemical phases, phase quantification and magnetic phenomena in polycrystalline materials.	Research	University of the Witwatersrand Rand Afrikaans University
Moisture in concrete	Investigations of the water movement in concrete during curing. The radiography method enables the *in-situ* following of the water distribution and concrete porosity.	Post-graduate project	University of Cape Town
Geology	Study to determine effective porosity and permeability of mineral ores.	Research	CURTIN University of Western Australia
Lectures	Lectures in non-destructive analysis methods of welded structures.	Training	South African Institute of Welding
Awareness creation	Intensive informative sessions on the beneficial uses of radiation supplemented by guided tours to SAFARI-1 gallery, over pool area and beam line facilities.	Excursions	Secondary school level Tertiary level

able information is provided on development and effectiveness of autofrettage processes [9] and the associated reverse yielding at the bore of thick walled steel tubes. Theoretical predictions of the extent of plastically yielded material regions were verified through direct measurement by taking the widths of the Bragg peaks as a gauge.

4.3.4. *Concrete industry.* The high contrast of water with respect to other materials in a thermal neutron beam is applied to the study of capillary water movement during the curing period of cast laboratory concrete samples. Depending on the speed of the process, this inspection can be done dynamically. The NRAD method furthermore enables the profiling of porosity over a slab of concrete.

4.3.5. *Geological industry* Recent applications of NRAD are in exploration geophysics and mineralogy, to study fluid flow dynamics in mineral rocks [10,11]. A study in collaboration with an Australian university is currently underway at SAFARI-1, to examine the porosity and permeability of various mineral ores from abroad. By incorporating PGNAA quantitative elemental analysis and distribution profiles can also be measured.

5. Format of collaborative academic projects

Unique capabilities have been established at the beam lines of SAFARI-1, where specialised high technology methods are now available to the fundamental and applied sciences. At NDIFF the applications extend from the fundamental sciences of physics and chemistry to mechanical engineering. At NRAD the fields of application predominantly cover the applied sciences and engineering disciplines. Whereas at PGNAA fundamental physics and applied sciences are covered.

The emphasis has been to attract students to pursue studies in radiation science and technology. This effort extends from undergraduate through to doctoral levels and research specialists. To stimulate student interest, training activities encompass vacation work, undergraduate projects, post-graduate research and participation in course work. Most notable, in this regard, is the M.Sc. programme in Applied Radiation Science and Technology (MARST) at the University of the North West. This could be paraphrased as "creating an awareness among future clients". A gradual drive to address the awareness needs of pre-higher education sector is also supported through school scientific excursions.

Renewed relationships with academic institutions have had to be nurtured to re-instill confidence and capabilities and these are frequently demonstrated through feasibility studies. This is systematically bearing fruit with the number of collaborations increasing. Table II illustrates the format of projects that have so far evolved from this initiative with academia.

6. Conclusion

It is evident that SAFARI-1, the research reactor at NECSA, plays a significant role in the national and international industrial arena. Some inroads to the local industry have been made, but there is still much room for improvement if the following hurdles can be overcome:

(a) Radiation technology must become a consideration for the local industry, based on an awareness of the technology available at NECSA,
(b) Physicists and engineers must break down the wall of isolation between them to serve technology development together.

The institutional role of SAFARI-1 comprises opportunities in research, training of students, and the inherent value addition to industrial product development. To establish vibrant research activities, the user community needs to be expanded. Obstacles to be overcome include the identification of the right partners, the deployment of SAFARI-1 facilities by the Higher Educational Sector for self-initiated research, acceptance of the new technologies and logistics of reaching the facilities.

Emphasis now is to act as a catalyst between industry and academia through provision of unique high-technology facilities.

References

1. De Beer, F. C. and Strydom, W. J. (Nondestr. Test. Eval. **16**, 163 (2001).
2. "Neutron Radiography (4). Proceedings of the Fourth World Conference; San Francisco, California, USA", (Edited by J. P. Barton), (Gordon and Breach Science Publishers, Pennsylvania, 1994).
3. "Frontiers of Neutron Scattering", (Edited by A. Furrer), (World Scientific, 1999).
4. Ashbaugh, C. E., Gems Gemology **24**, 196 (1988).
5. Von Ammon, W., Nucl. Instr. Meth. Phys. Res. **B63**, 95 (1992).
6. Hill, M. J., *et al.*, IEEE Trans. Electron Devices **23** , 809 (1976).
7. Baligna, B. J., "Neutron Transmutation Doping of Semiconductor Materials", (Edited by R. D. Larrabee), (Plenum Press, New York 1984), p. 167.
8. Louw, P. A., Robertson, D. G. and Strydom, W. J., Trans. Am. Nucl. Soc. **70**, 1041 (1994).
9. Venter, A. M., de Swardt, R. R. and Kyriacou, S., J. Strain Analysis **35**, 459 (2000).
10. Middleton, M. F. and Pázsat, I., Explor. Geophys. **29**, 512 (1998).
11. Middleton, M. F., Pázsat, I. and Solymar, M., (To be published in J. Non Destructive Testing Evaluation).