Research Reactors in Africa

A directory

2020 Edition

IAEA
International Atomic Energy Agency
Atoms for Peace and Development

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Introduction

The year 2019 marks Africa's sixty-year involvement with nuclear technology, dating from the initial criticality of the Democratic Republic of the Congo's TRICO I research reactor at the University of Kinshasa. Egypt and South Africa soon followed, signalling the commitment of countries in the continent to providing researchers with access to modern nuclear analytical techniques and irradiation capabilities. Twelve research reactors have thus far been built in eight countries throughout the continent, all of which are Member States of the International Atomic Energy Agency (IAEA).

Africa's research reactors are a vital component of the societal role played by nuclear science and technology; they provide neutrons to probe materials for structural integrity, to manufacture semiconductors through transmutation doping, to create radioisotopes for medical and industrial diagnostics and life-saving cancer treatments, to address pollution issues, and to assist farmers in crop selection and land use. Research reactors also support nuclear data and improve our knowledge of the subatomic world. They are typically regarded as being a starting point for national nuclear power programmes and as being essential to power reactors, since they can be used to train scientists and engineers and to provide experimental capabilities for studies of material damage, radiation shielding and waste containment. The services offered by research reactors often lead to the establishment of safe and efficient operation and maintenance, as well as improved safety culture and security culture.

Eleven research reactors currently exist across the African continent, covering a wide power range, from 0.1 kW to 22 MW. Common designs include General Atomics' TRIGA model and the miniature neutron source reactor (MNSR). Other, unique, designs exist, as shown in the table below.

Country	Facility name	Type	Thermal power (kW)	Neutron flux ($cm^{-2}\,s^{-1}$)
Algeria	NUR	Pool	1000	5.0×10^{13}
	Es-Salam	Heavy water	15 000	2.0×10^{14}
Democratic Republic of the Congo	TRICO II[1]	TRIGA Mark II	1000	3.0×10^{13}
Egypt	ETRR-1[1]	Tank WWR	2000	3.6×10^{13}
	ETRR-2	Pool	22 000	2.7×10^{14}
Ghana	GHARR-1	MNSR	30	1.0×10^{12}
Libya	IRT-1[2]	Pool, IRT	10 000	2.0×10^{14}
	TNRC	Critical assembly	0.1	1×10^{7}
Morocco	MA-R1	TRIGA Mark II	2000	7.1×10^{13}
Nigeria	NIRR-1	MNSR	34	1.2×10^{12}
South Africa	SAFARI-1	Tank-in-pool	20 000	4.0×10^{14}

The utilization profile differs across these reactors. For example, Morocco's MA-R1 reactor is used extensively for neutron activation analysis (NAA), while Algeria's facilities are mostly used for neutron-based materials research. South Africa's SAFARI1 is one of the five main producers of the radioisotope molybdenum-99 (^{99}Mo) and is a leader in neutron transmutation doping of silicon. Nigeria's research reactor is central to the country's Centre for Energy Research and Training, as is Ghana's research reactor to its National Nuclear Research Institute. Cooperation among the nuclear research facilities in Africa increases capabilities while harmonizing research, operation and best safety practices. Collaborative programmes can facilitate commercially viable radioisotope production, improve quality control in analytical utilization, broaden research endeavours and enrich valuable training curricula. Increasing numbers of MSc and PhD theses relying on the research offered by these reactors attest efforts in Africa to integrate higher education into research reactor science. Note: TRICO I, in the Democratic Republic of the Congo, is in permanent shutdown. Pelinduna-0, in South Africa, has been decommissioned.

1 In extended shutdown.

2 In temporary shutdown as of November 2019.

Africa's research reactors are well positioned to support socio-economic development. Standard of living increases in a given area tend to directly correlate with increasing energy demand. Although nuclear energy generation is under consideration in more than ten African countries, South Africa is currently the sole African state with a nuclear power station and intends to develop greater future capacity. Some Member States operating research reactors, for example Algeria, Egypt, Ghana, Morocco and Nigeria, consider research reactors to be a stepping stone for a future nuclear power programme, taking advantage of Africa's vast uranium resources. States without research reactors, such as Kenya, Senegal, Tunisia and Zambia, have planned research reactor projects targeting direct products and services markets, which will also serve as a trajectory towards commercial nuclear power. Other countries, such as the United Republic of Tanzania, are considering their first research reactor projects or planning the construction of additional research reactors. Nigeria, for example, is planning a second research reactor for radioisotope production, industrial science and nuclear power plant workforce training, among other uses. Several African countries are already taking advantage of the IAEA's Internet Reactor Laboratory (IRL) project for nuclear education and training; Morocco replaced France as host of IRL transmissions for Africa in 2018.

This brochure summarizes the current capabilities of Africa's research reactors, highlighting services that benefit a wide range of stakeholders, including universities, hospitals, research institutes, state ministries, nuclear power plant staff, mining industries, and agricultural and environmental organizations. These reactors use modern analytical techniques supporting research, manufacture of products for commercial applications, and training of future operators and researchers. Research reactors on the African continent offer great capacity for cooperative efforts in these areas. The information in this brochure is only a snapshot of these research reactors — their important role in nuclear science and technology to benefit society can only be inferred.

Algeria

Technical Characteristics

The Es-Salam reactor is a 15 MW multipurpose heavy water research reactor located in Birine. It is owned by Algeria's Atomic Energy Commission (COMENA) and operated by the Birine Nuclear Research Centre (CRNB). Commissioned in 1992, it is used as an experimental and training tool for nuclear techniques and reactor physics. It provides a high-quality thermal neutron flux and is equipped with several irradiation positions.


Es-Salam research reactor building

Technical Features

- Tank-type research reactor with a power of 15 MW
- Cooled and moderated by heavy water with a graphite reflector
- Six horizontal beam ports, including a thermal column and 45 vertical irradiation positions
- Maximum thermal neutron flux of 2×10^{14} $cm^{-2}s^{-1}$
- Continuous operation during the first three weeks of the month, with the remaining week reserved for maintenance

Products and Services

The Es-Salam research reactor is dedicated to the production of radioisotopes, scientific research, materials testing and training of technical and scientific personnel. The research and analytical laboratories associated with the reactor have qualified personnel and state-of-the-art equipment capable of performing multiple concurrent projects.


Delayed neutron counting laboratory

NAA continues to be one of the most utilized capabilities of the reactor. The laboratories dedicated to NAA have analysed both short, via a pneumatic system, and long lived radionuclides using traditional irradiation locations.

Irradiation and analytical services

- Pneumatic system for NAA and delayed neutron counting
- Neutron radiography facility (static and dynamic) for processing and non-destructive testing of materials
- NAA laboratories for trace element determination by direct comparison and k_0 methodologies

Research and Development

- Neutron diffraction facility equipped with a closed cycle coolant system using a helium liquefier for investigating material properties
- Thermal hydraulic loops: high pressure/temperature and low pressure/temperature
- Hot cells for destructive and non-destructive testing of irradiated materials
- Core physics and thermal hydraulic calculations
- Instrumentation and control design
- Numerical modelling and simulation
- Safety studies
- Nuclear data analysis
- Optimization of nuclear techniques


Neutron diffraction facility

Education and Training

- Reactor operation
- Reactor physics and nuclear technology
- Nuclear instrumentation and control
- Nuclear safety and radiation protection

Neutron radiography facility

Future Capabilities

In order to expand the analytical capability of the facility, several new projects are under development while the reactor is temporarily shut down. Analytical enhancements and developments include:

- Upgrading the neutron diffraction facility in order to study residual strain for academic and industrial applications;
- Implementing prompt gamma NAA for analysis of geological and atmospheric samples; and
- Producing radioisotopes for medical and industrial applications.

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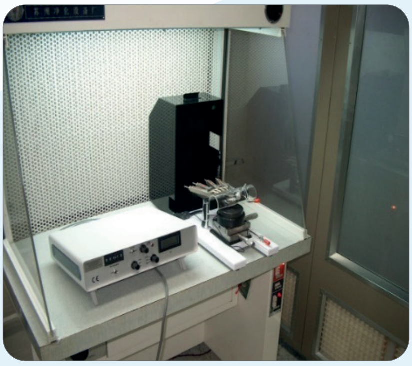


Four-point probe

Algeria

Technical Characteristics

Located near Algiers, the NUR research reactor is an open pool 1 MW research and training reactor, which was commissioned in March 1989.

NUR facility

The reactor is primarily used for:

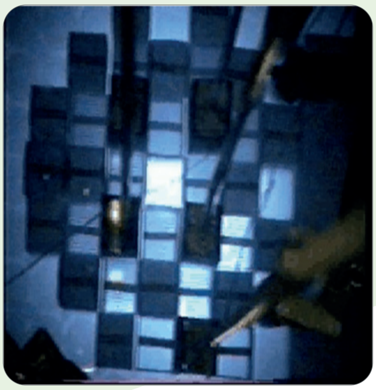
- Training operators and university students;
- Conducting studies and experiments in physics and reactor technology;
- Development and utilization of nuclear techniques;
- NAA;
- Neutron reflectometry;
- Neutron radiography;
- Small angle neutron scattering (SANS); and
- Production of radioisotopes and radiopharmaceuticals (at laboratory scale).

Technical Features

Reactor block

- Pool-type, 1 MW research reactor
- Materials testing reactor (MTR) plate-type fuel enriched to 19.75%
- Cooled and moderated by light water with a graphite reflector
- Neutron flux of 10^{13} cm^{-2} s^{-1}
- Four radial and one tangential beam tubes
- Two vertical irradiation positions
- Two fast pneumatic transport systems
- One hot cell and one transfer cell

Products and Services



Reactor core

Various research and development activities in the field of nuclear engineering are conducted by scientists and technical staff to enhance the utilization of the facility. The NUR reactor is a valuable tool at both national and regional level. It can be used to implement research and development programmes and will contribute to introducing a national nuclear power programme in Algeria.

Education and Training

- Nuclear engineering
- Reactor physics and operation

Research and Development

- Nuclear data analysis
- Nuclear technique optimization
- Materials science

Irradiation and analytical services

- NAA
- Radioisotope production (at laboratory scale)
- Quality control of radiopharmaceuticals
- Technetium kits
- In vivo and in vitro radiopharmaceuticals
- Monoclonal antibodies
- Neutron beam applications (SANS, reflectometry, neutron radiography, among others)

Universal cell

Future Capabilities

Several projects aim to optimize the utilization and availability of neutron techniques and applications, such as:

- Increasing the reactor power to 3.5 MW;
- Studying the use of neutron guides to improve the signal-to-noise ratio around the reflectometer and SANS spectrometers;
- Increasing the utilization of functional and proven nuclear techniques, such as NAA and neutron radiography; and
- Implementing a laboratory for the production of radioisotopes and radiopharmaceuticals.Contact Information

Technetium kits

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Egypt

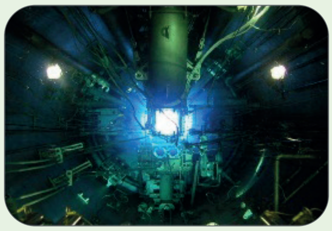
Technical Characteristics

Egyptian Testing Research Reactor-2 (ETRR-2) is a multipurpose research reactor located at the Nuclear Research Centre in Inshas, near Cairo. Its first criticality was achieved in 1997. The key aspects of ETRR-2's design are its flexibility and potential for modification to accommodate future needs and technology.

ETRR-2 building

Technical Features

- Open-pool type research reactor of 22 MW thermal power with a beryllium reflector and low enriched uranium fuel
- A total of 26 irradiation positions with a maximum core thermal flux of 2.73×10^{14} $cm^{-2}s^{-1}$ at the cobalt irradiation device
- Cooled and moderated by light water
- Currently operable and licensed for operation at full power
- Three radial and one tangential neutron beam tubes
- Two fast pneumatic transport systems for fast irradiation used in NAA
- Two irradiation positions for silicon doping and large sample activation analysis
- Several hot cell facilities for radioisotope processing, irradiated sample handling, inspections and materials testing
- A wide range of experimental and production facilities to meet the requirements of various utilization groups, including universities, research institutes, industry and medical organizations



Main pool

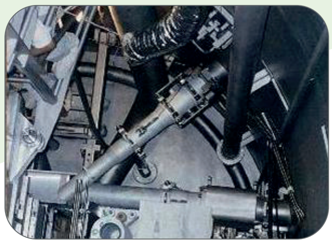
Products and Services

The reactor can support continuous full-power operations for 15 consecutive days without refuelling. The personnel are qualified to support longer operation times and trained to perform all the operations listed below at the highest safety and quality standards.

Materials testing hot cell

Research and Development

- Research on neutronic and thermal hydraulic calculations and modelling in support of reactor dosing, safety analyses and new applications
- Research and development in neutron tomography
- Analysis of samples
- Research on neutron beams for fundamental materials research and various applications



Beam tubes

Irradiation and analytical services

- Sample irradiation for analysis of different samples using NAA for geological, environmental and other medical applications
- Production of iodine-131 (^{131}I) and ^{99}Mo/technetium-99m(^{99m}Tc) generators for medical uses and other special radioisotopes, including chromium-51 (^{51}Cr), iridium-192 (^{192}Ir) and iodine-125 (^{125}I)
- Semiconductor production using neutron transmutation doping (NTD) for the irradiation of silicon ingots (with a diameter of 5 inches and length of 11 inches)
- Gemstone treatment (for example, topaz production, of around 200 kg per month)
- Irradiation of reactor component materials

Education and Training

- Training activities and workshops in radiation protection, quality management, core calculations and modelling, thermal hydraulics and research reactor safety
- Education and training for university students

Other

- Installation of sealed sources in gamma cameras for nuclear imaging
- Maintenance of gamma cameras and radiation protection devices

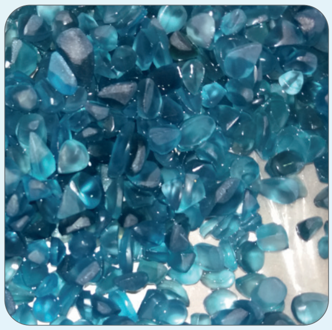
Isotope production, in particular, plays an essential role in the development of Egypt's national medical service. For example, ^{131}I and ^{99m}Tc generators are widely used to diagnose and treat thyroid cancer.

Silicon ingots are also relevant for the semiconductor industry and are widely used in commercial production.

Nuclear education, training and capacity building are important for Egypt, as the country has recently announced plans to embark on a nuclear power programme in 2020. Current reactor stakeholders vary, from research institutes and universities to industrial and medical organizations.

99Mo and fission 131I production


Silicon ingots for semiconductors


Blue topaz coloured by irradiation with neutrons

Future Capabilities

The administrators of the reactor and the respective Egyptian authorities fully support further utilization and implementation of a strategic plan for enhancing the sustainable development of ETRR-2. Projected modifications include:

- Development of in-core irradiation for ^{192}Ir production;
- Increase in capacity for ^{131}I and ^{99}Mo production based on neutron capture;
- Further development of NTD for the silicon facility; and
- Research and development in neutron beam applications, including the installation of a prompt gamma NAA facility and neutron scattering experiments.

Contact Information

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Ghana

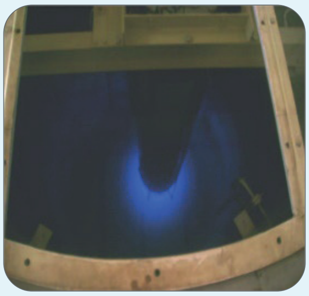
Technical Characteristics

The MNSR in Kwabenya, Accra is a low power research reactor similar in design to the Canadian SLOWPOKE reactor. MNSR reactors are operating in many countries, including China, the Islamic Republic of Iran, Nigeria, Pakistan and Syria, and are often used as a tool for NAA and capacity building. The construction, commissioning and operation of this reactor were authorized and inspected by the Ghana Nuclear Regulatory Authority with assistance of the IAEA. International safety assessment peer review and safety inspections have confirmed a high level of operational safety of the reactor since it began operating in 1994.

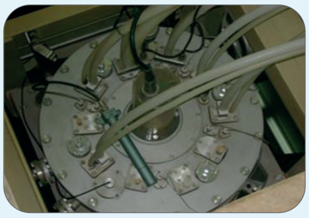
Ghana Research Reactor-1 (GHARR-1) research reactor building

Technical Features

- Tank-in-pool type 34 kW research reactor facility
- Fuelled with low enriched uranium (LEU)
- Small core heavily reflected on the sides and bottom with a beryllium alloy
- Cooled and moderated by light water in natural convection
- A single cadmium control rod clad with stainless steel is used for power regulation, compensation of fuel consumption, and reactor start-up and shutdown
- Ten irradiation sites arranged inside and outside the side annular reflector allow for multiple sample irradiations at different flux levels
- Maximum thermal neutron flux of 1.0×10^{12} $cm^{-2}s^{-1}$
- Two gamma spectroscopy systems plus detector equipment for qualitative and quantitative measurements
- Multi-elemental sample analysis facilities
- Education and training facilities for university students and nuclear engineers



Reactor in operation



Reactor vessel head

Products and Services

The GHARR-1 research reactor is utilized to support oil and aluminium manufacturing industries, research institutions, universities, governmental regulatory agencies, non-governmental organizations and individuals.

Research and Development

- Reactor physics, nuclear reactor core calculations and application-driven design, analysis and experiments
- Nuclear analytical techniques and nuclear waste management
- Geochemistry, hydrochemistry, soil fertility studies and mineral exploitation
- Radiation transport physics and shielding research.

Slanting tube for large sample NAA

Irradiation and analytical services

- Multi-elemental analysis of materials
- Analysis of borehole water, sediments and water from streams and rivers in mining areas
- Production of radioisotopes as tracers for petrochemicals and mining
- Industrial applications.

Education and Training

- Training nuclear scientists in reactor operation, physics and management to prepare for a potential national nuclear power programme
- Education for university students and other students in tertiary education through projects and research in nuclear science and technology

NAA is widely applied in multi-element non-destructive analysis in earth sciences, such as geology, geochemistry and geophysics; environmental monitoring and pollution assessment of air, water and soil samples; food and agriculture; health; medicine and pharmaceuticals; biology; and materials science. In Ghana, it has been applied to examine concentrations of trace elements in ancient pottery excavated from major archaeological sites.

Environmental pollution studies using environmental samples, such as sediments, soil, water and biological indicators, are examined at the GHARR-1 facility. One of the recent environmental studies involves the use of lichen transplants for monitoring vehicular traffic emissions in the country.

Analysis of ancient pottery using the neutron activation analysis technique

Future Capabilities

The reactor has been converted from high enriched uranium (HEU) to LEU fuel with international cooperation. It has the following objectives for future improvements:

- Increasing the quantity and variety of the short lived radioisotopes produced;
- Utilizing a new irradiation site (slanting tube) for larger sample (~5.0 g) treatments; large sample NAA will be applied to increase sensitivity under a low neutron flux;
- Supporting forensic investigation for security agencies;
- Increasing instrumental NAA for archaeological studies; and
- Installing detectors and integrating a gamma ray spectrometer into scanning devices, which will enable the rotation of cylindrical samples around the vertical axis during counting and will reduce the geometrical effects.

Quality control of petroleum products

Contact Information

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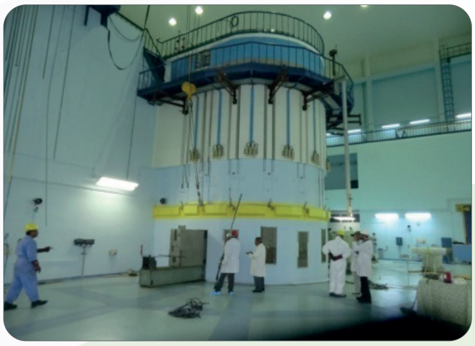
Libya

Technical Characteristics

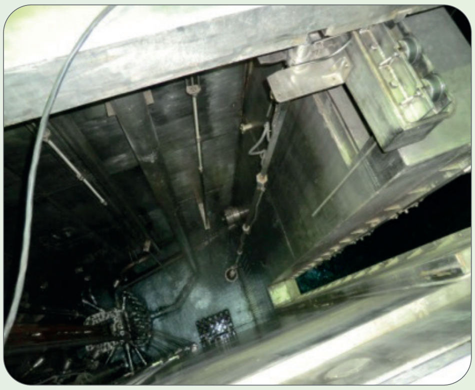
The IRT-1 research reactor was constructed at the Tajoura Nuclear Research Center in 1979 and began operation in 1981. In 2006, its fuel was converted from HEU to LEU. The facility is used for radioisotope production, research in nuclear science and technology, and education and training.



IRT-1 reactor hall

Technical Features

- 10 MW, pool-type research reactor
- Uses 19.7% enriched LEU fuel in IRT-4M cells
- Cooled and moderated by light water
- Beryllium reflector
- Maximum neutron flux of 10^{14} $cm^{-2}s^{-1}$
- Eleven horizontal channels, one of which is a double open-ended channel with a diameter of 150 mm
- Fifty sample irradiation positions
- A critical facility constructed as a mock-up of the reactor, with a maximum neutron flux of 10^{7} $cm^{-2}s^{-1}$
- A short irradiation facility and a laboratory for the analysis of long lived isotopes
- Vertical channels support radioisotope production



IRT-1 reactor hall during maintenance in 2013

Products and Services

Radioisotope Production

- Isotope production central to the facility's operation, yielding phosphorus-32 and ^{99m}Tc
- ^{131}I produced for local hospitals and sodium-24 used in the soap industry to improve chemical mixing;
- Bromine-82 produced and used in the oil industry as a radiotracer

Training facilities

Fundamental Research

- Nuclear physics
- Solid state physics
- Elemental analysis
- NAA for environmental studies

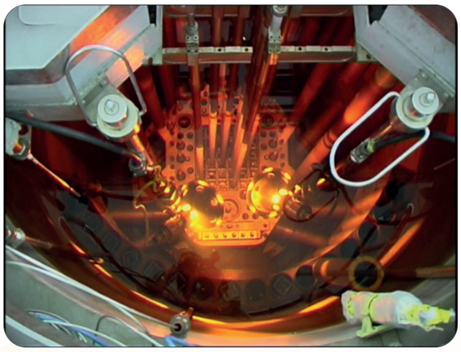
Education and Training

- Staff training
- Laboratory support for university students

Future Capabilities

Upgrades are foreseen to be made to the:

- Radioisotope production unit for medical and industrial applications;
- Safety protocol for operational safety and comprehensive maintenance;
- Control and safety system; and
- Facilities for short lived radioactive isotopes.



Critical facility core

Contact Information

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Libya

Hot cell

Morocco

Technical Characteristics

The MA-R1 research reactor facility is located at the Maâmora Nuclear Research Centre (CENM) of the National Centre for Nuclear Energy, Sciences and Technology (CNESTEN). The reactor building houses a TRIGA Mark II research reactor, which currently offers a maximum thermal power level of 2 MW but will be upgraded to 3 MW in the future. With its TRIGA reactor and fully equipped laboratories, CENM is Morocco's first nuclear installation with extensive capabilities, including the production of radioisotopes for medical, industrial and environmental uses, metallurgy, chemistry and the implementation of nuclear analytical techniques, such as NAA and non-destructive examination techniques. The TRIGA Mark II research reactor achieved first criticality in 2007.

Reactor facility building

Technical Features

- Steady state power rating of 2 MW
- A total of 101 TRIGA standard fuel elements with 8.5% uranium content enriched to less than 20%
- Five boron carbide control rods
- Reactor cooling by natural convection
- Rotary specimen rack assembly capable of simultaneously irradiating 79 samples
- Pneumatic transfer system
- One central experimental tube with a thermal flux of 7.08×10^{13} $cm^{-2}s^{-1}$
- Thermal column
- Three radial beam ports and one tangential beam port
- Hexagonal and triangular cut-outs

MA-R1 reactor

Products and Services

Most products and services at CNESTEN include analytical services related to environmental pollution, nutrition studies, mining, radioisotope production, and education and training.

NAA laboratory

Research and Development

- Nuclear instrumentation
- Neutronic and thermal hydraulic studies

Services and Products

- Instrumental and radiochemical NAA for geological and environmental samples
- Production of ^{131}I for medical applications
- Neutron radiography
- Prompt gamma NAA

Education and Training

- Host reactor for Africa's IRL transmissions
- Training and workshops in radiation protection, reactor physics and nuclear science and technology

Future Capabilities

Future enhancements to the reactor include the:

- Possible upgrade of thermal power to 3 MW;
- Installation of a SANS facility; and
- Installation of prompt gamma NAA and neutron radiography facilities.

Radiopharmaceuticals in the quality control laboratory

Contact Information

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Hot cell for radioisotope production

Training at the MA-R1 reactor

Nigeria

Technical Characteristics

The Nigerian MNSR, or Nigeria Research Reactor-1 (NIRR-1), is a small, compact and safe low power, tank-in-pool research reactor. In 2018, the reactor was converted to run on LEU instead of HEU. The MNSR was designed to be used in universities, hospitals and research institutes mainly for NAA, limited production of short lived radioisotopes and training. NIRR-1 is owned by the Nigeria Atomic Energy Commission, with the assistance of the IAEA. It is located at and operated by the Centre for Energy Research and Training at Ahmadu Bello University in Zaria, Kaduna State.

Reactor building

Technical Features

- 34 kW thermal power
- Neutron flux of approximately 10^{12} $cm^{-2}s^{-1}$
- One cadmium central control rod used for regulating power level, compensating fuel burnup and for start-up and shutdown
- Core consists of 333 fuel and 17 dummy elements arranged in a fuel cage of 10 concentric layers inside an annular beryllium reflector and resting on a lower beryllium reflector plate
- Runs on LEU fuel
- Moderated and cooled by light water through natural convection
- Ten irradiation sites — nine thermal and one epithermal
- Two built-in slant tubes

NIRR-1's first criticality on 3 February 2004

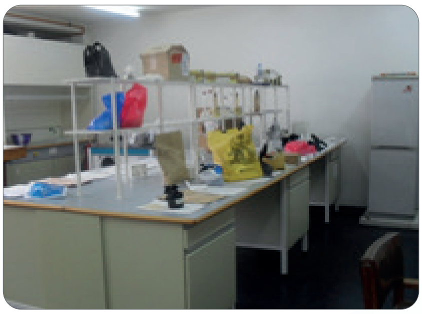
Products and Services

The reactor is used mainly for NAA and training. NAA is used in support of research, commercial irradiation and teaching programmes. Auxiliary systems such as pneumatic transfer (rabbit) systems provide additional NAA capabilities and are suitable for short- and long-period irradiation. The reactor is also deployed for nuclear physics and engineering training courses in the areas of, for example, reactor statics, reactor dynamics, thermal hydraulics, health physics and radiation safety.

The education and training programmes include nuclear reactor physics and engineering, geophysics, radiochemistry, health physics, radiation biophysics, nuclear instrumentation and waste management.

Analytical Services

- Determining nutrients and heavy metals in Nigerian and Ethiopian food and beverages, as well as bromine and iodine in medicinal herbs, by means of epithermal NAA
- Elemental analysis of flesh, bones and gills of a commonly consumed fish in Nigeria to improve human nutrition and health
- Use of k_0 epithermal NAA techniques for the determination of uranium, thorium and potassium in archaeological materials
- Geochemical and soil fertility mapping
- Determination of trace, minor and major elements in biological and geological samples



NAA sample preparation laboratory

Education and Training

- Undergraduate training
- Postgraduate training
- Training workshops

Reactor hall

Research and Development

- Neutronics analyses and thermal hydraulics studies
- Transient analyses of MNSRs under accident conditions
- Burnup calculations and fuel cycle analyses
- Effects of core excess reactivity and average temperature on the maximum operable time of NIRR-1
- Effects of temperature and control rod position on spatial neutron flux distribution
- Monte Carlo N-particle (MCNP) simulation of permanent cadmium-lined irradiation channels for improved utilization of commercial MNSR facilities
- MCNP calculations of neutron spectrum parameters in the irradiation channels
- Resolving discrepancies between the measured and estimated half-life of some radionuclides
- Measurements and evaluation of neutron-induced cross sections of threshold reactions
- Effect of germanium crystal size on energy resolution, efficiency and peak shape of high purity germanium detectors

Pneumatic transfer systems

Control systems

Future Capabilities

The production of short and medium lived radioisotopes is being investigated, and a radiochemical laboratory will be established for this purpose. Other areas to be further developed are:

- A study of the levels of toxic and heavy elements in wells, rivers, bottled water and public water supplies, as well as monitoring pollutants in air, water and sediments;
- Doping trace elements in ceramics and silicon wafers;
- Elemental analysis to examine evidence from crimes, such as hair, nail and serum samples, and to identify the age of pottery and metal artefacts;
- Development of methodologies for the analyses of trace elements in herbal medicine;
- Forensic and artefact studies; and
- Bulk sample NAA.

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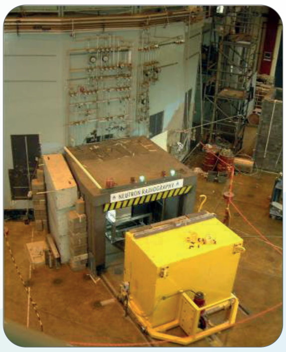
South Africa

Technical Characteristics

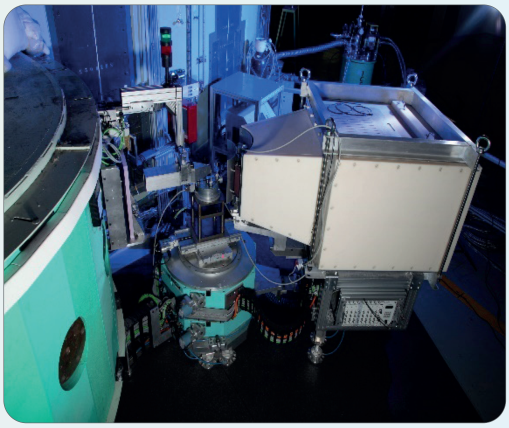
Built in 1961, the South African Fundamental Atomic Reactor Installation (SAFARI-1) is a pool-type MTR with a licensed operating power of 20 MW. Located at Pelindaba, near Pretoria, it achieved its first criticality in 1965. The site is equipped with a full range of facilities and services that support nuclear technology development and production. SAFARI-1 has regularly demonstrated its success by providing reliable services to South Africa, and is at the same time a very successful commercial enterprise.



Neutron radiography facility

Technical Features

- Pool-type research reactor with a power of 20 MW
- Utilization focused on commercial applications
- Operation with a fully converted core with LEU fuel and molybdenum LEU target plates since 2009
- Cooled and moderated by light water with a beryllium reflector
- Twelve core irradiation facilities with maximum neutron flux of 4×10^{14} $cm^{-2}s^{-1}$
- Wide range of support facilities, including an MTR fuel manufacturing plant, extensive hot cell facilities, radioisotope centre, pipe storage facility for spent fuel, two disposal sites for low and medium level radioactive waste and a radiochemistry laboratory
- Reactor operates 24 hours per day, 7 days per week, with more than 300 days per year at full power
- The SAFARI-1 quality, health, safety and environment management system is certified to ISO 9000 and ISO 14000 standards.

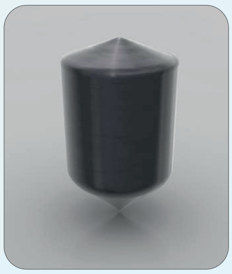


New neutron diffraction facility

Products and Services

Irradiation and analytical services

- Production of radioisotopes for medical application (for use nationally and for export), particularly ^{99}Mo and ^{131}I
- Neutron transmutation doping for silicon ingots
- Pneumatic and fast pneumatic systems for NAA
- Digital neutron radiography and tomography for various applications, such as oil and mineral exploration, civil engineering, archaeology, palaeoanthropology and nuclear waste research



Silicon ingot

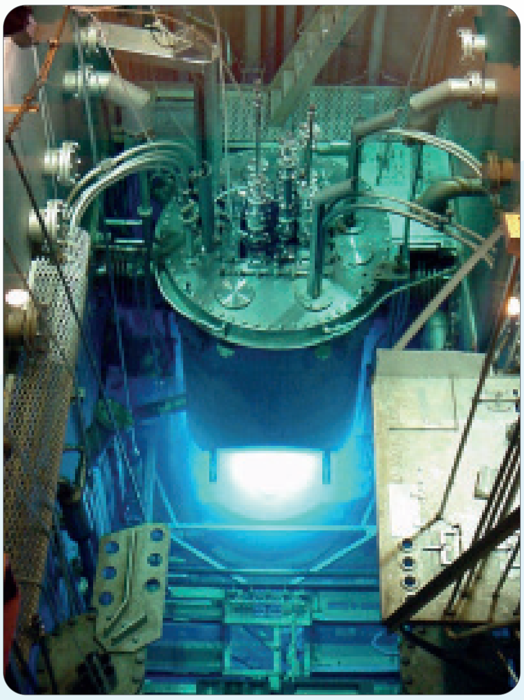
Research and Development

- Neutron diffraction for magnetic phase analysis, residual strain, chemical phase analysis, crystallography, magnetic phase analysis and nuclear materials research
- SANS for materials research
- Beam tube experiments and basic and applied research in physics and nuclear engineering

Education and Training

- All training related to the operation, management and applications of research reactors conducted by the Reactor Training Committee
- Organization of national, regional and international training courses and workshops
- Education and training for university students, including for MSc and PhD projects

The ^{99}Mo produced in the reactor naturally decays to ^{99m}Tc, which is used in four of every five diagnostic procedures worldwide and in an estimated 40 million procedures annually for detection and staging of heart disease and cancer diagnoses. Currently, SAFARI-1 is one of the world's five largest producers of ^{99}Mo. Although the global demand for ^{99}Mo is growing, SAFARI1 remains among the few reliable producers, participating in the supply chain of more than 50 countries worldwide.



Reactor core

Future Capabilities

Recent evaluations have indicated that an expected operational lifetime beyond 2025 is realistic. Over the past 52 years, the reactor has been continuously modernized to ensure the safety and reliability of structures, systems and components important to safety. Still, the successful commercial use of the reactor enables the constant development and improvement of the facilities and infrastructure, allowing for increases in utilization opportunities. Current developments include:

- An ageing management programme to upgrade various reactor structures, systems and components in addition to other improvement projects, which will enable an extension of its life up to 2030;
- SANS facility for applications in nano-powders, polymers, textiles for nuclear waste and nuclear materials research for academia and industry; and
- Neutron radiography facility upgrades.

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The Internet Reactor Laboratory

(Photo: IAEA)

The IAEA works with Member States to develop a variety of nuclear education and training programmes. One such project, launched in 2015, is the IRL, a cost-effective way to add an experimental component based on the use of a research reactor to university curricula where otherwise such an opportunity might not exist.

The IRL creates a virtual reactor in a remote location by linking a host reactor with university classrooms in other locations. Using data acquisition hardware and software installed in the host research reactor, real-time signals are sent over the internet to the participating classroom, where students are able to see the live display of the reactor's control panel. Using a video conference link, students can conduct experiments by asking the reactor operators in the control room to change reactor settings and see real-time output. This type of virtual training helps Member States that do not have an existing research reactor to develop a nuclear infrastructure for new nuclear power programmes.

Until 2018, students from the United Republic of Tanzania and from Tunisia participated in the IRL project through live transmissions from the French Alternative Energies and Atomic Energy Commission's ISIS research reactor. In 2019, Africa received its first host research reactor under the IRL initiative, when the infrastructure and accumulated knowledge and experience of Morocco's MA-R1 reactor was made available to other African countries through the IAEA. It became possible to use this reactor as a host for other African countries such as the United Republic of Tanzania and Tunisia.

(Photo: IAEA)

New Research Reactor Projects

Kenya

Research reactors will be key in Kenya's medium- and long-term plans for increasing the number of research and development programmes, which will enhance the country's capacity for implementing a nuclear power programme successfully and increase its capacity for national and industrial participation. Kenya is in the first phase of implementing its research reactor project and plans to commission its first research reactor between 2025 and 2028. Preliminary studies show that a research reactor could support education and training as well as industrial, medical and research applications in Kenya. Experimental capabilities for the proposed research reactor include education and training, radioisotope production, testing, NAA, material structure studies and transmutation effects.

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Nigeria

Nigeria has taken the decision to embark on the development of a multipurpose research reactor project to meet national requirements and has conducted a preliminary feasibility study in this regard. For more than ten years, Nigeria has safely operated a 30 kW (MNSR). However, due to the limitations in the capabilities of the MNSR beyond routine NAA and training, there is an increasing demand for a multipurpose research reactor. The new research reactor is primarily expected to provide services in the production of radioisotopes for use in medicine, agriculture, industry and education. The design of the research reactor will also take into consideration the possibility for future expansions.

As a further demonstration of its commitment to the research reactor project, Nigeria has signed an intergovernmental agreement, as well as a project development agreement, with a technical partner for the design, construction, operation and decommissioning of a multipurpose research reactor complex.

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Senegal

Senegal established, starting in 2018, a technical cooperation project with the IAEA entitled "Developing a National Nuclear Infrastructure for Establishing a Research Reactor". The objectives of the project were to develop regulations and prerequisites for establishing a research reactor and a nuclear power plant in Senegal.

The expected outcomes are the establishment of a research reactor for radioisotopes production, neutron activation analysis, research and development and the training of personnel for implementing the project.

Stakeholders involved in the project are:

- The Ministry of Petroleum and Energy;
- The Ministry of Higher Education and Research, which will undertake coordination of cooperation with the IAEA and the promotion of scientific research in Senegal;
- The Ministry of Environment and Sustainable Development, which will prepare and implement government policy to combat pollution and protect nature;
- The Ministry of Health;
- Cheikh Anta Diop University;
- The National Electricity Company, which is responsible for energy production, transportation and distribution;
- The Institute of Applied Nuclear Technology, which will coordinate all nuclear research activities; and
- The regulatory body, Radiation Protection and Nuclear Safety Authority, which is responsible for the general implementation of the government policy for radiation protection and nuclear safety; its mission revolves around three main objectives — regulation, monitoring and public information.

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United Republic of Tanzania

The United Republic of Tanzania has conducted a pre-feasibility study for a possible research reactor project and has concluded that a research reactor could be a highly useful tool for contributing to the country's scientific resources, improving health care, and increasing industrial and agricultural productivity. A reactor would also help decision-makers develop a comprehensive understanding of all the obligations and commitments involved in operating a research reactor.

Following this pre-feasibility study, extensive evaluations of the following will be conducted in order to raise awareness of the implications of a establishing a research reactor project:

- Time and cost of design, construction and commissioning;
- Safety and regulatory requirements;
- Resources required for operating and maintaining the facility, including fuel costs;
- Resources required for dismantling and decommissioning; and
- Costs associated with radioactive waste and spent fuel management, and disposal and regulatory requirements.

The prospective owner and operator of the research reactor will be clearly designated before embarking on this next phase. In preparation for a full-fledged feasibility study, it is important to ensure the availability of personnel with experience and knowledge to meet the requirements, analyse data and compile the feasibility study report from technical, socio-economic and legal perspectives.

The research reactor will potentially serve three main purposes. It will be a tool for education and training in reactor physics, reactor operations, nuclear safety, neutron physics, and radio and nuclear chemistry. The reactor could also serve as a source of neutrons of different energies. Finally, the prototype facilities would enable the maturity of nuclear technology and training to be demonstrated before full-scale power reactors are built.

Several possible options for applications depend on the stakeholders' needs and availability of funds. The projected attributes of the reactor include:

- Thermal power of up to 1 MW with natural convection cooling;
- Education and training, NAA, delayed neutron counting, neutron radiography, limited neutron diffraction, limited isotope production (not on an industrial scale), limited neutron beam applications, testing of nuclear instruments and detectors, and gemstone coloration;
- Estimated capital cost range of US $10–15 million;
- Estimated operation and maintenance costs of US $1–1.5 million per year;
- Fuel management accounting for a limited fresh fuel supply and spent fuel;
- 10–15 staff for operation and maintenance; and
- Decommissioning ('green field') will account for approximately 15% of the capital costs.

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Tunisia

In line with Tunisia's project of embarking on a nuclear power programme, the National Centre for Nuclear Science and Technology (CNSTN) plans to install a subcritical assembly to support the development of national human resources and perform applied research and development in the nuclear field. The subcritical assembly is to be located at the CNSTN site in Sidi Thabet, 35 km from Tunis, and will enable scientific research projects to develop an understanding of specific concepts relevant to nuclear reactor physics.

The subcritical assembly will contribute to the initial steps, including the enactment of new legislation and the establishment of a competent and independent nuclear safety regulator, needed for the development of the Tunisian nuclear power programme and related infrastructure.

The projected technical characteristics of the subcritical assembly include:

- A design that will provide operators and users with an inherently safe tool that is simple, reliable and easy to operate with minimum operation and maintenance requirements; parts of the subcritical assembly will also be easily accessible for demonstration, inspection and experimental purposes;
- A system that is fuelled with natural or low enriched uranium and moderated and reflected by light water; the reactor will be driven by an extraneous neutron source featuring a combination of plutonium and beryllium or americium and beryllium; the core will consist of several hundred fuel pins loaded into a water-filled vessel;
- A neutron source that will be driven by a pneumatic control drive into the reactor core; to shut down the reactor, the same source will be driven back to its storage flask;
- A reactor that is contained in a stainless steel tank1.0 m in height, with a 1.0 m inner diameter and a thickness of 10 cm; 144 low enriched uranium dioxide (4% ^{235}U) fuel pins are loaded into the water-filled vessel, with the fuel pins fulfilling an equivalent cylindrical volume of 20 cm in radius and 65.5 cm in height; the moderator contained in the vessel is deionized and distilled light water; and
- An extraneous neutron source of plutonium–beryllium characterized by an activity of 0.8 Ci and neutron intensity of 1.1×10^6 s^{-1}.

In addition to training and education, other activities and services will be performed at the CNSTN subcritical assembly, including conducting and developing specific scientific research in nuclear physics in cooperation with other, in particular foreign, institutes and universities.

Various nuclear experiments and measurements will be provided by the subcritical assembly, and at least one in-core irradiation position will be implemented for NAA and sample irradiation.

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Zambia

Zambia and many other countries in the sub-region have recently suffered critical power deficits arising from low water levels in natural water bodies caused by the effects of El Niño and from the lack of investment in alternative energy sources.

The President of the Republic of Zambia, Edgar Chagwa Lungu, announced during his inauguration that Zambia would pursue nuclear energy technology and its applications as part of a diversified sustainable energy mix to power Zambia's economy.

The nuclear energy power programme is envisaged to be undertaken over a period of between 10 and 15 years. The nuclear science and technology programme is aimed at creating synergies, capacity building and expertise to ensure that Zambia benefits from the peaceful uses of nuclear science and technology.

The programme will be undertaken in two main phases, in line with the IAEA's recommendations. The phased approach is appropriate because nuclear technology requires highly qualified personnel and a regulatory base to ensure safety and security.

In **phase one**, the Russian Federation will support Zambia to adequately prepare for the management and utilization of the nuclear facilities through the following:

- Training and skills development in the field of nuclear energy;
- Development of nuclear policy;
- Nuclear infrastructure assessment; and
- Construction of the Centre for Nuclear Science and Technology, which will house a 10 MW research reactor for the training of personnel for the nuclear programme.

In **phase two**, the Russian Federation will assist Zambia to conduct feasibility studies for a nuclear power plant.

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