

Key Technical and Safety Requirements for a new Research Reactor: The RA-10 Reactor Experience

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Abstract. A new multipurpose research reactor which will replace RA-3 reactor has been decided to be built in Argentina to satisfy the increasing national and regional demands for radioisotopes. The project, supported by the National Administration, started in 2010 and is planned to be operative in 2019. The expertise acquired in the country, in the design and licensing of nuclear reactors, encourages the National Atomic Energy Commission (CNEA) to face the challenge. INVAP S.E. is involved in the design of the reactor facility and related installations, and has been contracted for the supplying and assembly of SSCs.

Technical and safety requirements have been early established, based on the safety objectives, concepts and principles presented in the NS-R-4. Technical requirements are based on the utilization related requirements and in consistent reactor availability for the intended use.

Key requirements, considering as a guide, the structure and the contents of the IAEA Nuclear Energy Series No NP-T-5.6 are presented in this paper.

Key Words: research reactor, RA-10, safety requirements, technical requirements

1. Introduction

The RA-10 Research Reactor is a 30 MW multi-purpose open-pool type facility, with a compact square array core containing 6 internal irradiation positions and 19 MTR fuel assemblies. A heavy water reflector tank surrounds the core and houses the ex-core irradiation facilities. The core and the heavy water reflector tank are both placed in an open pool containing the light water coolant that flows upward. The irradiation rigs are independently cooled by means of the pools cooling system. Reactor shut down can be achieved by two independent means, which are the insertion of the six APs into the core, or the partial drainage of the heavy water from the Reflector Vessel.

The reactor is designed for the accomplishment of two main purposes:

- The continuous production of several radioisotopes, such as ⁹⁹Molybdenum, and ¹⁹²Iridium, among others; and Neutron Transmutation Doping in Silicon ingots.
- Perform several types of experiments, for what features thermal and fast neutrons in-core Irradiation Facilities, Pneumatic Rigs with a wide range of neutron fluxes, two Cold Neutron Beams provided by a Cold Neutron Source, two Thermal Neutron Beams, one particular Beam for a underwater Neutron radiography facility, one Power Reactor FAs testing Loop and a MTR FAs testing position.

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2. Key technical and safety requirements

2.1. Licensing and Siting

The Operating Organization (CNEA) developed a Licensing Plan in order to achieve the licensing conditions for the facility. Among other features, this plan includes all the regulatory documentation that must be met in the reactor design process.

In the frame of a Design Procedure that includes a Design Plan for each working structure, the corresponding documentation is included as design requirements that must be explicitly fulfilled. In this way, the “Design Evaluation” included in the PSAR could be easily performed and concluded.

Safety Analysis and the PSAR were elaborated by the Operating Organization based on the IAEA Safety Standards No SSG-20.

The site evaluation comprised collecting of all the safety relevant site information and developing site specific studies necessary to support the safety assessment. The site studies were elaborated in compliance with the IAEA Safety Requirements No. NS-R-3.

2.2. Safety and Radiological Design Requirements

The general nuclear safety objective for the RA-10 Reactor, adopted in conformance with the IAEA Safety Standard No NS-R-4, is to protect individuals, society and environment from harm by establishing and maintaining effective defences against radiological hazards in nuclear installations.

In order to achieve the safety objective, the project defines three main principles in the design:

2.2.1. Defence in depth

The application of the principle of defence in depth in the design of the research reactor provides a series of level of defence (provision of successive physical barriers, conservative design margins, inherent features, equipment and procedures, including on-site and off-site emergency procedures) which are aimed at preventing accidents and ensuring appropriate protection in the event that prevention fails.

2.2.2. Safety Functions and Safety Classifications

Safety functions are the essential characteristics functions associated with structures, systems or components (SSCs) that ensure the safety of the reactor.

Beside the three fundamental safety function, i.e., shutting down the reactor, cooling the reactor core components continuously and confining radioactive material inside the installation, safety functions related to: fission products barrier and configurations integrity, control and monitoring, reactivity regulation and shutdown, reactor protection, radiative material confinement, core cooling, services supplying, shielding, decay and purification and physical- protection were defined and classified based on their importance to safety. Safety functions were identified to ensure the effectiveness of each level of defence in depth. NS-R-4 safety functions list was used as reference.

All SSCs were classified based on their function and importance to safety [1]. The objective of a safety classification is to guarantee that, for all SSCs fulfilling safety functions, seismic, quality and reliability requirements, are adequate during design, construction and maintenance stages. From this classification criteria and requirements will be derived for the different engineering stages and for the reactor life stages.

The SSCs classification is based on considering: the defence in depth criteria, the safety functions each SSCs is called to perform, the consequences of the failure of any SSCs important for safety, the probability of each SSCs of being demanded to fulfil a safety function and the elapsed time after the occurrence of a Postulated Initiated Event in which the actuation of a SSCs is required.

2.2.2.1. Requirements

Requirements are assigned at four stages: related to function level, related to design level, related to equipment performance level and related to quality assurance, verification and maintenance level. The level of the requirements of each class is consistent with the importance of the SSCs related with the specific safety function to comply.

2.2.2.2. Safety Classes

Following a summary of the main characteristics of each safety class is described:

- Class A

SSCs which failure could provoke unacceptable consequences when required.

SSCs which failure could provoke unacceptable consequences and there is no Class A SSCs to cope with such failure.

Any SSCs which mitigation action is required to take the plant to a controlled state following a Design Basis Event or an Anticipated Occurrence.

- Class B

SSCs controlling and limiting relevant process variables.

Those SSCs whose failure demands the actuation of a Class A SSCs.

- Class C

Those SSCs that contribute to ensure Class A or B reliability.

Any auxiliary or process SSCs performing mitigation functions after a Beyond Design Basis Event.

2.2.2.3. Methodology for SSCs classification

- **Postulation of Initiating Events:** The methodology adopted is an iterative process. A good acquaintance of the installation is required as the first step for classification. From this understanding of the systems and processes an Initiating Events (IEs) list can be identified and postulated. The list is completed with information from IAEA Safety guides as well as local operational experience and international incident reports.

- **Safety functions identification:** From the postulated IEs list the required safety function can be derived applying the principle of Defence in Depth.

- **Safety function class assignment:** With the list of required safety functions they can be classified according to the class definition described previously.

- **Requirements per class assignment:** Assignment of a clear and good defined set of requirements to each class for the four stages described previously.

- **Safety function groups identification:** This implies identifying a SSCs related with the safety function to be performed.

- **Refinement of class assignment:** During the previous process it could be possible that new safety functions, requirements and even SSCs appear. The procedure of identifying and

classifying safety functions must continue until a complete and coherent list were obtained for each engineering stage.

2.2.3. Acceptance criteria and design rules

Acceptance criteria were established for Operational States (OSs), for Anticipated Operational Occurrence (AOOs), for Design Basis Events (DBEs) and for Extended Design Basis Events (EDBEs) [2].

For OSs, radiation exposure on workers and members of the public is kept below prescribed limits and as low as reasonably achievable. For DBEs, no radiological consequences from accidental sequences are allowed on members of the public.

For EDBEs and BDBEs, all accident sequences were evaluated and demonstrated to comply with the regulatory established acceptance criteria, i.e. their annual occurrence probability combined with the corresponding effective dose must meet a limiting risk level according to the national regulations.

Engineering safety features (ESFs) are provided as essential safety characteristics to meet this criterion. ESFs are SSCs provided to prevent, limit or to mitigate the consequences of failures or human errors resulting in AOOs, DBEs or EDBEs.

Depending on the abnormal conditions they are designed to cope with, ESFs are classified into Design Basis ESFs and Extended Design Basis ESFs.

Design Basis ESFs implement fundamental safety functions to act in response to those AOOs having dynamic characteristics that surpass normal operating control provisions and to DBEs. RA-10 ESFs include:

- The Reactor Protection System
- The First Shutdown System
- The Core Natural Circulation Circuit
- The Experimental Device Natural Circulation Circuit
- Autonomous Area Radiation Monitors located at selected areas.

Extended Design Basis ESFs realize fundamental safety functions upon the occurrence of EBDEs, i.e. selected beyond the design basis events and severe accidents considered in the RA-10 design on the basis of engineering judgment and the results of deterministic and probabilistic analyses. Extended Design Basis ESFs are designed taking into account the requirements and environmental conditions imposed by the EBDEs they are intended to deal with. The main purpose of the Extended Design ESFs is to enhance safety design characteristics of the RA-10 reactor by expanding the reactor capabilities to withstand, without unacceptable radiological consequences, plant conditions more severe than those of DBEs, i.e. events involving multiple failures and severe accidents. Extended Design Basis ESFs included in the RA-10 design are:

- The Second Shutdown System
- The Emergency Water Injection System
- The Long Term Cooling System
- The Confinement
- The Post-Accident Monitoring System
- The Emergency Control Room
- The Standby Power Supply System
- The Evacuation Alarm Systems

For the design of SSCs, acceptance criteria are established in the form of engineering design rules. These rules include requirements related to the classification of the SSCs that are important to safety.

An extensive external event safety assessment was conducted based on the information provided by the site evaluation. This safety assessment allowed ensuring that the reactor include the provisions to withstand the conditions imposed by the site characteristics, including the effects of extreme external events either natural, such as seism or flooding, or man induced, such as aircraft impact. In this assessment the characterization of external events provided in the site evaluation were the input and it was evaluated whether the design adequately copes with the postulated external events. Acceptance criteria for this assessment are set in terms of compliance of the design with recognized design standards.

2.3. Utilization related design requirements

Utilization related requirements provided by the user were consolidated and restricted, resulting in the following utilization related design features: neutron activation analysis, radioisotopes production, neutron transmutation doping, neutron beam applications for material structure studies and neutron radiography.

The 6 in-core irradiation positions are focused on material testing such as neutron damage and corrosion studies. The two central positions (F1, F2) present an intense fast neutron flux, while the four positions placed at the corners (T1-T4), show a reactor spectrum flux [3].

The ex-core irradiation facilities include: radioisotopes production, silicon doping, pneumatic tubes, a fuel-testing pressurized loop, an in-pool neutron radiography and beam extraction tubes: two thermal and two cold from a cold neutron source.

The irradiation facilities distribution inside the reflector tank is shown in FIG. 1.

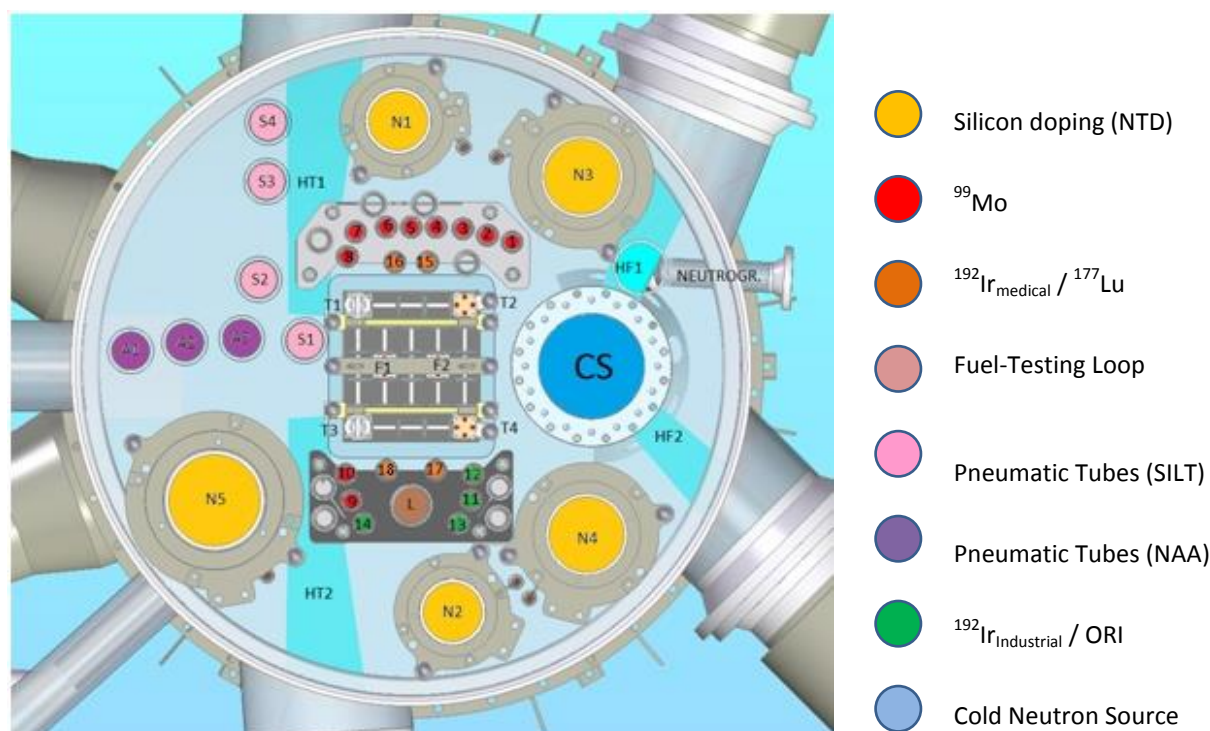


FIG. 1. Facilities distribution in the reflector tank.

2.3.1. Molybdenum-99

Mo-99 is produced by fission of low enriched uranium targets. The approximate irradiation time is 5 days under a thermal flux level between 1 and 1.5×10^{14} n/cm²s. The targets can be extracted during normal reactor operation. Ten irradiation positions, containing 8 targets each, are required. However, it might be upgraded to 12 targets per irradiation position. The irradiation device consists of a target holder containing 4 positions each. Mo-99 positions are shown in FIG. 1 (in red, positions 1 to 10).

2.3.2. Iridium-192

Ir-192 is obtained by means of metallic iridium activation. For the industrial use, the required flux is between 1 and 1.5×10^{14} n/cm²s, and for medical applications $>1.8 \times 10^{14}$ n/cm²s is needed. A maximum of 4 irradiation devices positions are considered. The irradiation device model is shown in Figure 3. Wire-shaped medical iridium is placed in 10-centimeter-long container tubes, obtaining a total of 1.2 m per device. For industrial use, iridium foils are placed inside aluminium tubes, separated by aluminium discs. FIG. 1 shows positions for industrial use (green, positions 11 to 14) and for medical use (orange, positions 15 to 18).

2.3.3. Lutetium-177

Lu-177 is produced by irradiating Lu-176 evaporated in glass tubes. These tubes have the same flux requirements as medical Ir-192 and share the same positions. See positions 15 to 18 shown in orange in FIG. 1.

2.3.4. In-core Facilities

For material testing applications, samples will be irradiated inside in-core capsules or devices. These devices can be placed in the center of the core (positions F1 and F2) for high fast flux irradiation (5×10^{14} n/cm²s) and at corners (positions T1 to T4) for reactor spectrum flux (3×10^{14} n/cm²s).

2.3.5. Fuel Loop Irradiation Facility

The Fuel Testing Loop Facility is a pressure containment placed inside the reflector close to the reactor core (FIG. 1, “L” position) designed to test power plant fuels rods in long-term irradiation and transient situations. Linear power densities between 200 and 600 W/cm are planned with PWR pressure and temperature conditions.

2.3.6. Silicon irradiation - NTD

The neutron transmutation doping process will be implemented by placing silicon ingots in the reflector tank. The Si ingots require a neutron flux in a range of 1×10^{13} n/cm²s to 4×10^{13} n/cm²s and the irradiation period will vary upon the target resistivity requested.

In order to provide a high quality semiconductor material, commercial requirements of NTD include achieving high axial and radial uniformity of the dopant agent in the silicon targets.

RA-10 will have 5 positions for NTD, two for 6” ingots, two for 8” ingots and one position for a 10” ingot. The ingots positions are labeled as N1 to N5 in FIG. 1.

2.3.7. Pneumatic System

The pneumatic irradiation facilities are intended for material science studies through neutron activation analysis (NAA) and long term irradiation (SILT). Also it might be beneficial for developing new radioisotopes.

The samples are placed in a small capsule into the nitrogen pneumatic pipeline which can carry the capsule from the laboratory to the reflector tank.

The technical requirement for this system is an average thermal flux between $1 \text{ n/cm}^2\text{s}^1$ and $2 \times 10^{14} \text{ n/cm}^2\text{s}^1$. A diversity of spectral ratios is accomplished by placing the rigs at different distances from the core. The required spectral ratio should be between 2 and 500. Positions in the reflector tank for NAA are labeled as A1 to A3 and for SILT as S1 to S4 in FIG. 1.

2.3.8. Cold Neutron Source

The neutron cold source, "CS" in FIG. 1, consists of an 18-litre moderator chamber containing Liquid Deuterium at a temperature of 20K, which is placed into a cylindrical vacuum container. Cold neutrons are extracted through two helium-filled tubes, which communicate the CS with both experimental facilities placed in the reactor face and the neutron guides which conduct these neutrons to the experiments hall.

2.3.9. In-pool Neutron Imaging Facility

An in-pool neutron imaging facility will be available for studying irradiated material and devices. Its main purpose will be to support the fuel loop irradiation facility by performing non-destructive tests.

This facility will have a quality factor $L/D > 150$ (where L is the distance from the neutron source to the sample and D is the source dimension) with a minimum effective area of $15 \text{ cm} \times 15 \text{ cm}$ and a thermal neutron flux, $\phi_{th} > 1 \times 10^7 \text{ n/cm}^2\text{s}$.

2.3.10. Neutron beams

The thermal neutron beams consist of two extraction tubes that communicate a region of a high thermal neutron flux in the heavy water reflector with the experiments and guides where such neutrons are required. For all beams a minimum of $1 \times 10^9 \text{ n/cm}^2\text{s}$ thermal or cold flux is required at the instruments position.

2.4. Others key technical requirements

The availability of the reactor is required to be consistent with its intended use. In order to assure an availability of 80% for the reactor and of 90% for the facilities, availability factors were assigned to SSCs considering its need for the reactor or facilities operation. These availability factors resulted in a quality classification for all ESCs.

The spent fuel storage facility is required to provide space for the volume of ten years operation (20 cores). The facility will be placed in the Reactor Service Pool and will be compatible with a transportation cask for carrying the spent fuel to a general storage facility.

The discharge burnup is required to be larger than 45%.

The absorber plate's lifetime is required to be larger than 5 years [4].

The reactor full-power day fuel cycle is required to be 29 days.

3. Conclusions

Key technical and safety requirements for a new research reactor have been outlined considering the RA-10 Reactor Project experience.

These requirements have been fully specified in conformance with the local regulations, the IAEA standards and the utilization related design objectives.

Other technical requirements related to reactor availability and spent fuel storage have also been addressed.

4. References

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