DEVELOPMENT OF THE RRR COLD NEUTRON SOURCE FACILITY

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ABSTRACT

This paper describes some general design issues on the Cold Neutron Source (CNS) of the Replacement Research Reactor (RRR) for the Australian Nuclear Science and Technology Organisation (ANSTO). The description covers different aspects of the design: the requirements that lead to an innovative design, the overall design itself and the definition of a technical approach in order to develop the necessary design solutions.

The RRR-CNS has liquid Deuterium (LD2) moderator, sub-cooled to ensure maximum moderation efficiency, flowing within a closed natural circulation Thermosiphon loop. The Thermosiphon is surrounded by a CNS Vacuum Containment made of zirconium alloy, that provides thermal insulation and a multiple barriers scheme to prevent Deuterium from mixing with water or air. Consistent with international practice, this vessel is designed to withstand any hypothetical energy reaction should Deuterium and air mix in its interior.

The applied design approach allows ensuring that the RRR-CNS, in spite of being innovative, will meet all the design, performance and quality requirements.

Keyword: *Cold Neutron Source, Research Reactor*

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1. RRR-CNS GENERAL DESCRIPTION

Fast neutrons produced in the reactor core are moderated by the heavy water in the Reflector Vessel leading to high neutron fluxes in the thermal energy range. The fraction of cold neutrons (up to 10meV) in this spectrum is very small and thus, it is necessary to produce an appropriate energy spectrum shift to get high fluxes at the required low energies.

The proper spectral shift is obtained by means of a liquid Deuterium (LD_2) moderator located close to the thermal flux peak in the Reflector Vessel, its function being to reduce the energy (or temperature) of neutrons. The liquid Deuterium flows by natural circulation around a continuous loop that includes a heat exchanger (namely the Thermosiphon). The liquid is sub-cooled to a temperature below saturation at all points of the loop, ensuring maximum moderation efficiency.

Deuterium is liquefied and kept in liquid state within the closed Thermosiphon loop, with the heat exchanger and a cooling jacket fed with cryogenic Helium at about 19 K.

The "cold" neutrons (E < 10 meV) are then transported through the neutron guides into the Reactor Beam Hall and Neutron Guide Hall, where research instruments are located. The CNS Moderator System containing the Deuterium is totally contained within a gas blanket, to prevent Oxygen from reaching the Deuterium. This blanket gas is monitored to give an early warning of leakage. The Thermosiphon is surrounded by a zirconium alloy CNS Vacuum Containment that provides thermal insulation and extra protection in the event of a Deuterium barrier breach, to prevent Deuterium from mixing with water or air. Consistent with international practice, this vessel is designed to withstand a hypothetical energy reaction should Deuterium and air reach critical concentrations in its interior. The CNS Vacuum Containment, plus the CNS In-Pile Assembly, which includes the CNS Thermosiphon, the CNS Reflector Plug, the CNS Flange and all the connections to the CNS Connected systems serving the CNS, is called the CNS In-Pile Thimble.

The "multiple barriers" concept is fully applied to the CNS design. The entire CNS Moderator System is double-walled with an inert gas in between performing a blanketing function. Within the In-pile Thimble, this double wall encloses all of the Thermosiphon and is filled with Helium from the CNS Refrigeration Cryogenics System. In turn, the Thermosiphon loop is fully contained in the CNS Vacuum Containment, which acts as a physical barrier between the reactor environment and CNS systems.

The Deuterium Moderator is, therefore, isolated from the reactor core environment (the heavy water Reflector Vessel) boundary by three successive engineered barriers, each having a continuous early leak detection system between them. In consequence, although physically close to the core, the CNS can be considered effectively outside the Reactor System. Table 1 presents the main RRR CNS characteristics and Table 2 approximate values of main operating parameters.

Table 1: Main Cold Neutron Source Characteristics

Parameter	Value
Reactor power	20 MW
Moderator type	Liquid Deuterium
Moderator volume	20 litres
Moderator Temperature	~ 23 K
Moderator circulation / cooling	By natural circulation in a sub-cooled Deuterium Thermosiphon, He cooled.
Heat removal capacity	5000 W
Average Cold Neutron Flux in Cell	$7.3\ 10^{13}\ \cdot cm^{-2} \cdot sec^{-1}$
Cold Neutron Flux at Reactor Face	$1.4\ \ 10^{10}\ \ cm^{-2} \cdot sec^{-1}$
Moderator Cell material	AlMg5 Alloy
VC material	Zr-Nb Alloy
VC design pressure	1.6 MPa
Commissioning	Year 2005

Table 2: Normal Operation mode – approximate nominal operational parameters

Parameter	Nominal Value
Heat load on the Moderator Chamber	4300 W
D2 pressure	330 kPa
He T to the Chamber	19 K
He T to the HX	19 K
Total cooling He flow rate	160 g/s
He pressure after the TS	150 kPa
Vacuum around the Thermosiphon	$1.3 \cdot 10^{-2}$ Pa

Figure 1 shows a 3D view of the CNS IN-Pile Thimble. Figure 2 shows the position of the CNS within the reactor pool with the core, associated structures and cold beam tubes.

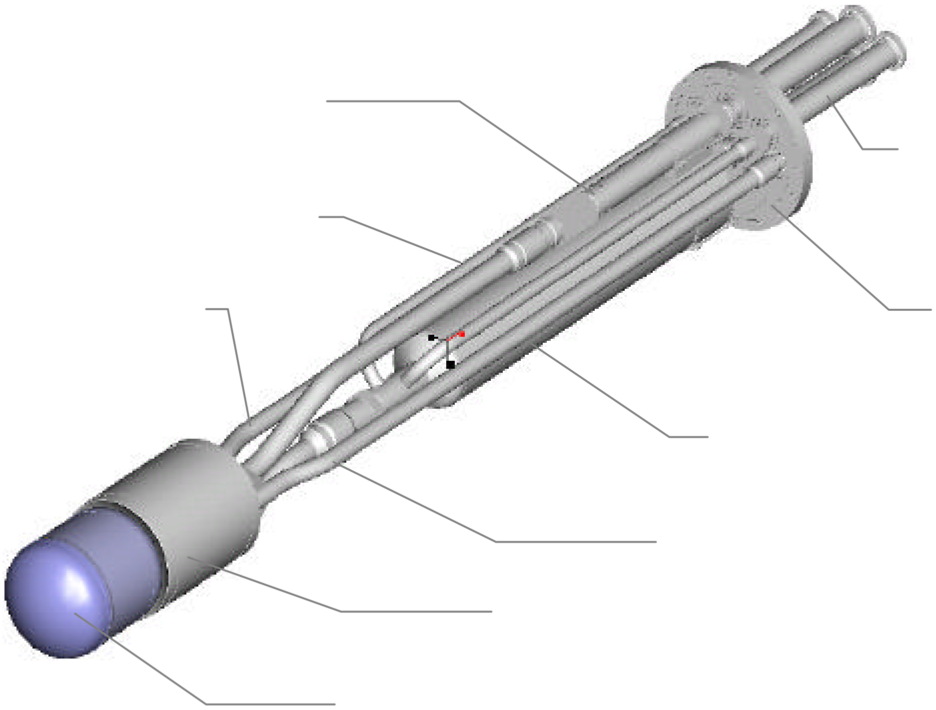

Figure 1: CNS In-Pile Thimble

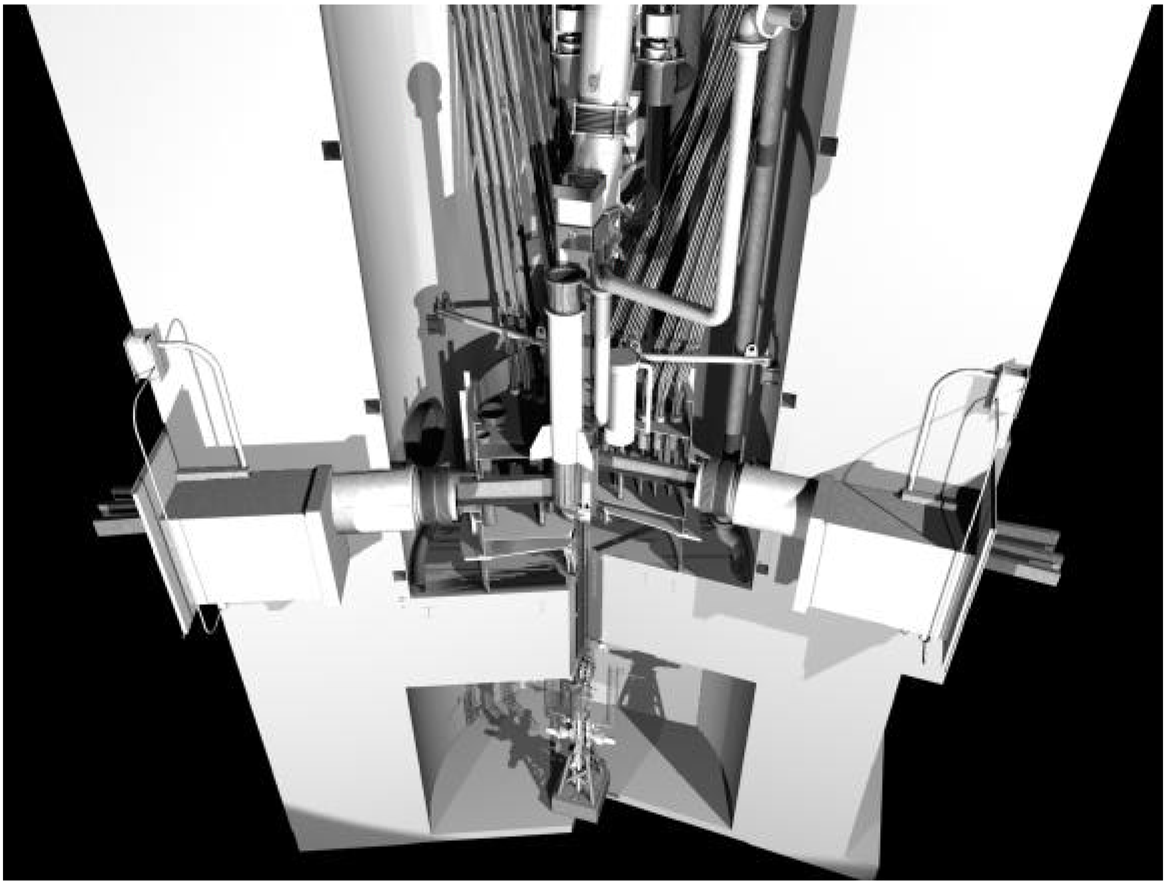

Figure 2: 3D-model of the CNS within the reactor pool.

2. DESCRIPTION OF MAIN CNS COMPONENTS

The Liquid Deuterium fills the CNS Moderator Cell, a vessel of about 20 liters. It features a Helium filled Displacer, which is a vessel of about 2 liters, and is surrounded by the Helium Jacket. There is a gap between the Moderator Cell and the Helium Jacket to circulate cryogenic Helium providing appropriate cooling. The entire set, the Moderator Cell plus the Helium Jacket plus the Displacer, is called the Moderator Chamber and is made of aluminum alloy.

The Moderator Chamber is the lower part of the Thermosiphon loop where a total of about 30 liters of moderator are contained and flow by natural circulation. The upper part of the Thermosiphon loop includes a Heat Exchanger made of stainless steel.

A heavy water filled Reflector Plug is located between the Moderator Chamber and the Thermosiphon Heat Exchanger. Its associated function is to minimize the up streaming of neutrons through the void created by the Thermosiphon.

The Moderator Chamber, the Reflector Plug, the Thermosiphon Heat Exchanger and all connected piping is linked by supporting structures to the CNS Flange, which also provides the interface connections to the external CNS support systems. This complete assembly is called the CNS In-pile Assembly.

The In-pile Assembly is located inside the CNS Vacuum Containment; a pressure vessel made of zirconium alloy, and designed to cope with any incident in the Thermosiphon.

3. OPERATION OF THE CNS

The CNS has two operation modes compatible with reactor operation, Normal and Standby.

During “Normal Operation” mode (NO), the CNS Refrigeration Cryo-System (CNS-RCS) provides the cooling power necessary to liquefy the Deuterium and keep it sub-cooled by circulating cryogenic Helium through the Heat Exchanger and the Helium Jacket.

In the “Standby Operation” mode (SO), the CNS-RCS removes the heat load of the CNS Moderator Chamber material by circulating Helium at ambient temperature through the Helium Jacket. The Deuterium reaches a condition of approximately the same temperature in all the Moderator System, which has most of its volume given by the Deuterium Buffer Tanks.

A third CNS operation mode, namely the “Halt Operation” (HO) mode, is only compatible with the reactor shut down. It is with the CNS-RCS stopped and at ambient temperature; the Deuterium is, as in the Standby mode, mainly in the Deuterium Buffer Tanks.

4. CNS CONNECTED SYSTEMS

Figure 3 shows a simplified diagram of the CNS Connected Systems.

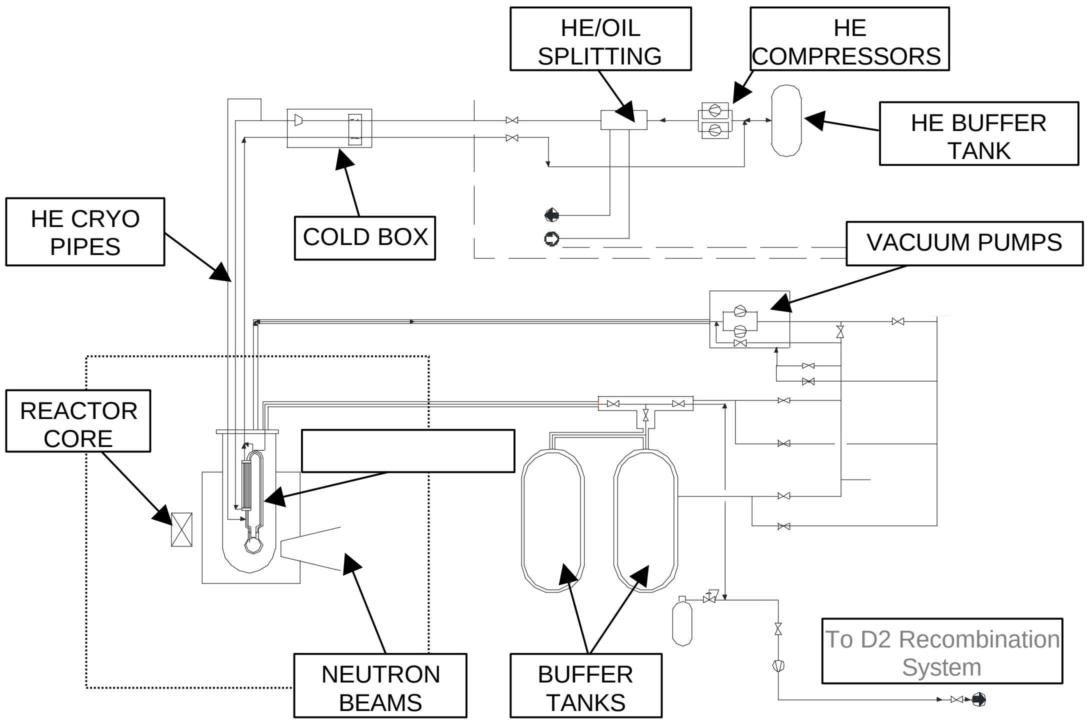

Figure 3: Simplified Process Diagram of the Cold Neutron Source

Refrigeration Cryo-System: The heat load on the CNS Thermosiphon coming from neutron and gamma-ray heating is removed by the CNS-RCS, which circulates cryogenic Helium through the heat exchanger and the Helium Jacket of the Moderator Chamber, with adequate heat removal capacity to cope with all operational states of the CNS.

CNS Moderator System: It is a closed system containing the Deuterium inventory required for the CNS operation, making on-line reloading unnecessary. The system comprises two Deuterium Buffer Tanks connected to the Thermosiphon loop through tubing and a valve manifold, with no active elements such as pumps or compressors. The flow from the Buffer Tanks is established when Deuterium liquefies and the pressure of the entire system decreases. The whole system has a double wall construction to incorporate the gas blanketing function around the entire Deuterium volume, which provides a means of detection and control of Deuterium leaks.

CNS Vacuum System: It provides a vacuum volume around the cold parts of the CNS acting as a thermal insulation and providing a physical barrier against the intrusion of liquids or gases into the In-pile Thimble. The CNS Vacuum System is a closed system surrounded by an inert gas blanket, with two high-vacuum pumping sets; each of them has a primary oil-free vacuum pump and a turbo-molecular pump. The vacuum pumps discharge through the blow-down line into the Reactor Hall. Constant pumping of the CNS Vacuum Containment is not necessary during normal operation, only in the event of vacuum set-point deviation.

CNS Gas Blanketing System (Helium and Nitrogen): It insulates the Deuterium pipes from contact with air and/or water, and controls Deuterium leakage. The blanket gas pressure is such as to ensure that any Deuterium leakage is into the blanket gas and not vice versa. The blanketing system allows the control of any Deuterium leakage through the blanket pressure control and gas analysis. Sampling and diaphragm valves allow blanketing gas to be fed and monitored in each blanketing enclosure.

CNS Heavy Water System: The CNS Heavy Water System provides a cooling flow for the Reflector Plug located above the Moderator Chamber. The system takes the flow from the Reactor Facility Reflector Cooling and Purification System.

5. DEVELOPMENT APPROACH

There are requirements on the RRR CNS that lead to the need of developing innovative design solutions:

- The RRR CNS System shall be optimised to maximise the yield of neutrons in the direction of cold neutron guides CG1-3.
- The peak in the cold neutron flux energy spectrum at the reactor face shall be about 4.2 meV. The cold neutron flux at this position should de greater that 1.4E+10 $n \cdot cm^{-2} \cdot sec^{-1}$
- The RRR CNS is required to have a Stand by Operation mode, allowing for the partial unavailability of some of the Refrigeration Cryo-System components.
- The liquid Deuterium is required to be sub-cooled in all the bulk of the Moderator Cell, the volume maximized and the shape optimized in cold neutron production.

Taking the refrigeration cryogenic power as an input parameter, the challenge is to solve the design of a Moderator Cell that, compared to existing similar facilities, has an increased operating pressure and an additional Cooling Jacket, without decreasing the moderating volume.

This implied making compatible the thermal-hydraulics of naturally circulating Deuterium in the Moderator Cell with the nuclear heat deposition, and the mechanical implementation of the vessels with a shape achieving the cold neutron fluxes requirements.

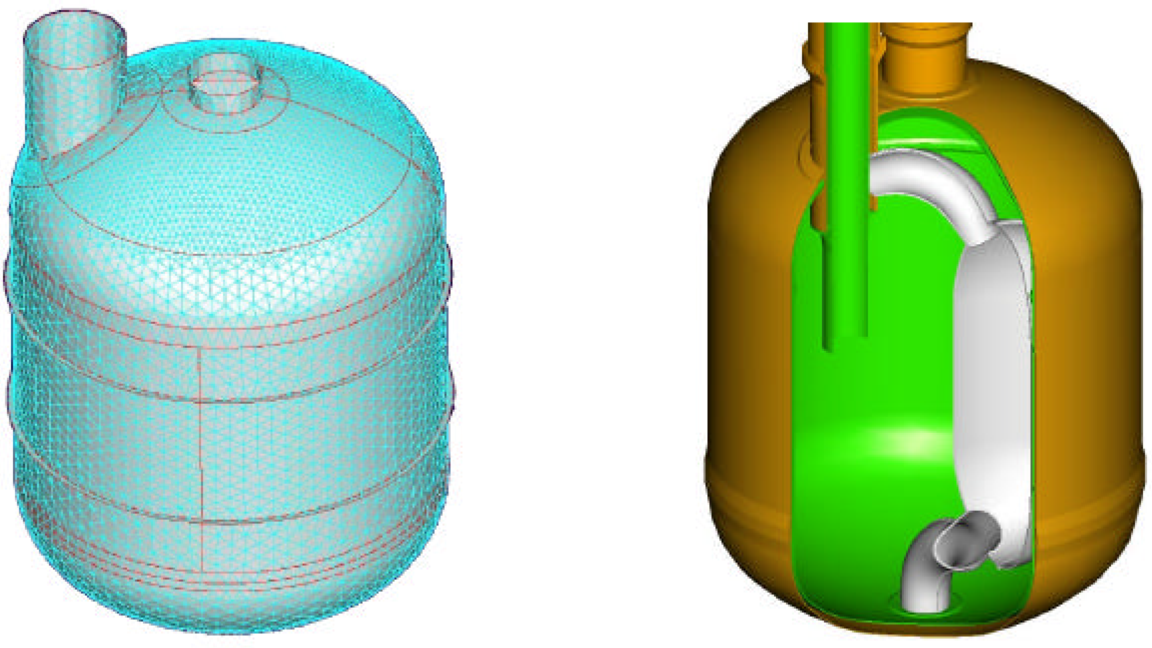

Figure 4: Moderator Chamber Geometry.

Neutronics Design: The RRR CNS neutronics design defined the basic requirements on the system. It was essentially focused on:

- Positioning of the CNS into the D2O Reflector Vessel to accommodate to the available refrigeration capacity. It implied a careful selection of materials to be used as well as to manage the strong interfacing with all other reactor’s irradiation facilities.

- Maximizing the cold neutron flux while tuning the neutron spectrum, defining the Moderator Chamber geometry, including the Displacer shape and position. It also implies managing the interfacing with the mechanics design of the chamber.

To perform these tasks on a comprehensive comparative basis, appropriate design models and tools to were developed. MCNP (Ref /1/) was used as the reference neutronics code, and appropriate cross section sets based on ENDF/B-VI (Ref /2/) were developed and verified.

3D Fluid Dynamics in the Moderator Cell: In order to verify that the Deuterium fluid in the Moderator Cell is sub-cooled, and that the overall behaviour, in terms of streaming, turbulence, patterns, is compatible with the expected heat removal, a set of 3-D fluid dynamics studies was performed.
The modelling of the tri-dimensional time evolution of the fluid inside the Moderator Cell was performed by a CFD (Computer Fluid Dynamics) code. The code is a development of the Computational Mechanics Group (CAB-CNEA) and has been adequately benchmarked.

A fully coupled, mixed convection run was undertaken to get an indication of the flow and thermal structure, taking into account all the phenomena involved at the actual operating conditions.

Results of instantaneous temperature (for Normal Operation conditions) range from 19.5 K to 24.5 K. In terms of velocities a strong upwards jet on the wall opposite to the inlet is evident, as well as low temperatures near the bottom wall produced by jet's spreading. No trapped region is observed, which would appear as a high-temperature region. In fact, the highest temperature away from the walls is about 23 K.

Fig. 5 shows the predicted temperature at the walls, where colours range from 19.5 K (inlet, taken as reference) and 29.5 K. It is interesting to observe the cylindrical wall near the Displacer on the side opposite to the inlet tube where the "wake" of the Displacer produces relatively high temperatures. However, even these are reached only in small, localized regions, and are not greater than 29.5 K.

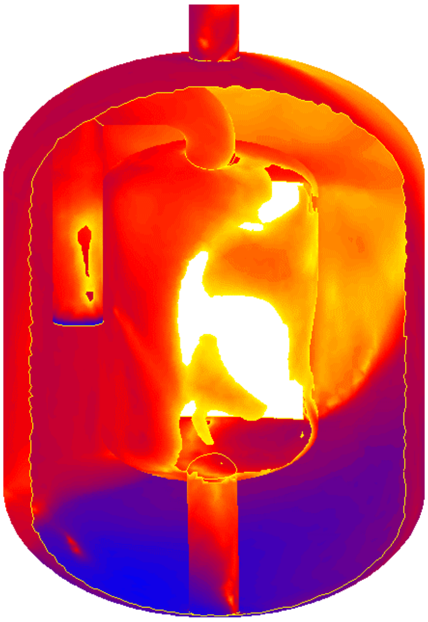

Figure 5: Temperature at the Aluminium walls as predicted by the fully coupled simulation.

Mechanical Design: It combined a strength calculation as a guideline for defining basic dimensions of the Thermosiphon and the Moderator Chamber, with computer code stress analysis of the detailed geometry. In general, detailed stress analysis was performed for those components where compliance with the standards through simplified models (strength calculations) compromises the performance goals. The tools used for this task are commercial codes as COSMOS/M and ANSYS.
Nevertheless, during the Detailed Design stage several tests beyond the ones defined by the QA and QC manufacturing program are foreseen: Design Support Tests and Prototyping Tests.

Design Support Tests: are intended to ensure the viability of the design and additionally to provide design tools for improving analytical accuracy. They include experimental activities on models of the Moderator Chamber or its components, and may produce feedback with significant impact on the Moderator Chamber design.

Prototyping Tests: a full-scale model of the In-pile Assembly will be made and tested before the CNS fabrication for ANSTO reactor. The radiation heat release will be imitated by electrically heating de Moderator Chamber, and a Helium Cryogenic System of similar capacity to the one to be supplied will be used. They include two different types of tests.

- The Prototyping **Qualification Tests** are performed to verify and analyse the CNS In-pile Assembly performance, in terms of hydraulics and heat removal, using boundary conditions as complete as possible. Exact operating points should be determined for each operational mode, measuring all relevant variables including some that will not be measured when assembled in the Reactor Facility.
- The Prototyping **Engineering Tests** are carried out to produce information on the system behavior (not necessarily related to performance) providing feedback and/or verification on certain design data in order to allow for adjustments or optimization.

6. CONCLUSIONS

Nowadays, the classic definition of a Research Reactor (RR) as “a source of free neutrons” is still applicable. But, in hand with the new scientific and technological advances, the RRR-CNS project imposes specific requirements on these “free neutrons”. The design target is still focused on the amount of available neutrons and their energetic and spatial distribution, but it has to be reached within the framework established by the last standards on safety levels adopted by the Nuclear Industry, as well as by the highly demanding additional services required to the reactor. These pose on the engineered systems new levels of demand on reliability and availability.

The design approach briefly described in this paper allows ensuring that the RRR-CNS, in spite of being innovative, will meet the design, performance and quality requirements. This is achieved combining the best available technical experience, the use of state of the art design tools, with a careful planning of the development program well inserted within the engineering activities. At the same time, the approach ensures that only minor adjustments, if any, would be needed during the RRR-CNS commissioning.

Therefore, it may be concluded that the RRR-CNS has a safe and high performance design, which fulfills all the fluxes and the operational requirements.

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