EXPERIMENTAL LOAD: CORE & REACTOR BLOCK DESIGN AND SAFETY OF RESEARCH REACTORS

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ABSTRACT

To achieve the overall optimisation in both CAPital and OPerational EXpenditures, (CAPEX and OPEX) the design of the core and reactor block of Research Reactors (RRs) is mainly driven by three types of requirements:

- The experimental load requirements: research reactors have a wide range of applications and combination of applications,
- The easiness of operation: given various practical, historical or cultural approaches throughout the world,
- The safety requirements: in some cases, stringency of application of requirements is balanced with the hazard potential of research reactors compared to NPP.

This paper focuses on the multipurpose RRs from 2 main origins (MTR and physical research reactor) that can perform part or the whole of the following applications <1>: radioisotope production (including Mo-99), testing (materials and nuclear fuels), material structure studies (including Cold Neutron Source), Silicon transmutation doping and neutron activation analysis. It presents the various architectures of the reactor blocks and cores from designer perspectives.

To be more specific, after some introductory remarks and presentation of the stakes, the main topics developed in this paper will cover:

- A discussion of the converging and diverging interests between the various experimental programs,
- A presentation of the main overall reactor block architectures: mainly a comparison between Be reflector- and Heavy water reflector-oriented designs,
- A discussion of the main choices during the design, depending on the experimental load objectives and the interconnections between CAPEX and OPEX: fuel assembly, moderator, coolant, reflector, shutdown systems, core housing and other structures,
- Operational considerations: usability, flexibility, adaptability of the various designs,
- The safety and licensing approach regarding the implementation of experimental devices in the core and the reflector of a research reactor such as Jules Horowitz Reactor (JHR).

1 Introduction

After the review of the pool-type research reactors design <2> and the overview of the contributions of previous projects to the design of new research reactors <3>, this paper focuses on applications to meet utilization requirement. In addition, it gives some insight about the modifications of existing core and reactor blocks.

TechnicAtome, as the former engineering department for research reactors of the French Atomic Energy Commission (CEA), has practices of research reactors design, operation of nuclear facilities at Cadarache (see <4> for example) and modifications of existing reactors (see the current FOREvER project <5>).

Table 1 lists the research reactors as well as core and in-pool modifications (including Instrumentation and Control) in which TechnicAtome has been involved.

Nature	Year	Designation	Type	Utilization
New builds	On going	RES	PWR test reactor - France	• Training & Neutron Physics
	On going	JHR	100 MW pool type reactor France	• Material Testing Reactor • Radio-isotope production
	2005	MAAMORA	Research Centre hosting a TRIGA Mark II reactor Morocco	• Multidisciplinary nuclear research center • In operation
	1988	RNG	PWR test reactor France	• Training & Neutron Physics • Shutdown in 2005
	1980	ORPHEE	U-Al 14 MW pool type neutron beams reactor France	• Fundamental research • Radio-isotope production • In operation
	1978	PHEBUS	UO2 38 MW pool type reactor France	• Safety studies • Shutdown in 2007
	1971	RHF	58 MW High Flux neutron beams Reactor France	• Fundamental Physics • 1.5 10^{15} n/cm²/s • In operation
	1966	OSIRIS	U3Si2 70 MW pool type reactor France	• Material Testing • Radio-isotope production • Shutdown in 2015
	1966	ISIS	U3Si2 700 kW pool type reactor - France	• Training & Neutron Physics • In operation
	1965	EOLE	UA1 Zero Power pool type Reactor - France	• Fundamental research • In operation
	1963	CABRI	UO2 25 MW pool type reactor - France	• Safety studies • Up to 1.3 10^{17} n/cm²/s • In operation
	1962	AZUR	Zero Power pool type reactor - France	• Training & Neutron Physics • In operation
	1959	MINERVE	U-Al Zero Power (0.1 kW) pool type reactor - France	• Fundamental research • In operation
Installed Base: Core & In Pool Modifications - Instrumentation & Control	On going	FOREvER project	See <5>	See <5>
	2008	CABRI	UO2 25 MW pool type reactor	Reactor block replacement (core housing, pressurized vessel for experimental device, safety tube, primary circuit)
	2005	ORPHEE	U-Al 14 MW pool type neutron beams reactor	Replacement of the safety I&C
	2004	AZUR	Zero Power pool type reactor	New digital I&C
	2003	CABRI	UO2 25 MW pool type reactor	Seismic reinforcement
	2003	OSIRIS	U3Si2 70 MW pool type reactor	Replacement of the core grid and the pool safety handling device
	1994	RHF	58 MW High Flux neutron beams Reactor	High Flux Reactor, Replacement of Heavy Water Tank
	1992	SILOE		Pool liner, I&C and primary circuit refurbishment

Table 1: Research reactor and core & in-pool modifications in which TechnicAtome (previously CEA's department) has been involved

For the reactors design, this paper focuses on the following topics:

- The characteristics of the main experimental devices and converging and diverging interests between them,
- The main overall core and reactor block architectures: mainly a comparison between Be reflector and Heavy water reflector oriented designs,

- The main choices to be made during the design, depending on the experimental load objectives and the interconnections between CAPEX and OPEX: fuel assembly, moderator, coolant, reflector, shutdown systems, core housing and other structures,
- Some operational considerations: usability, flexibility, adaptability of the various designs,
- The safety and licensing approach regarding the implementation of experimental devices in the core and the reflector of a research reactor such as JHR.

2 Experimental loads

As regards application with a significant impact on the core and reactor block design, the main applications are neutron beams for science and industry (with or without Cold Neutron Source (CNS) or Hot Neutron Source (HNS)), radioisotope production for medicine and industry (with both inert or fissile targets), Neutron Doping Transmutation (mainly for Silicon doping), Material and Fuel testing for nuclear industry, Neutron Activation Analysis and Prompt Gamma Neutron Activation Analysis. Usually, for the reactors of significant power, utilization for training has no direct impact on the core and reactor block design but an indirect one via the reactor operational schedule.

These applications can be in competition between them from various points of view:

- Competition for the usable volume: experimental devices have specific geometries (for the in-core part and for the upper and lower ex-core parts of the device) and also a range of neutron flux perturbation. These perturbations depend on the required flux quality for the other surrounding experimental devices and on the core or reflector neutron characteristics. For example, figure 1 illustrates the difference between the perturbation due to 2 different experimental devices in a Be reflector,
- Competition for the neutron flux and the neutron fluence, including steadiness of the flux along the core lifecycle: for example, neutron beam users require a steady flux and radioisotope production can induce a scheduled decrease of the power during loading/unloading of the targets,
- Competition for the economic efficiency of the application: the direct costs of the components, the indirect costs due to the licensing process and the different level of financial incomes induce different contribution to CAPEX and OPEX,

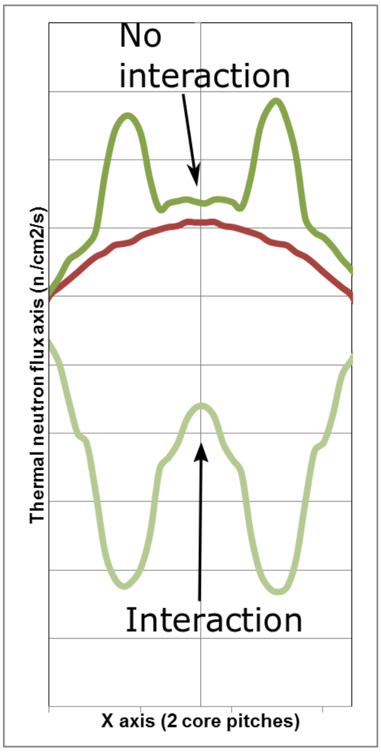

Figure 1: Example of potential interaction between 2 in-reflector devices.
Upper curve: 2 “inert” MTR devices with no interaction
Lower curve: 2 absorbing devices with interaction between them
Medium curve: “unperturbed” flux

- Competition from safety point of view: the experimental devices have different impacts on core reactivity, peaking factors, nature of the postulated initiating events. Some irradiation devices, like fission Molybdenum targets and Fuel Test Devices contain fuel, and/or, for Material and Fuel testing device, materials like Na or NaK with water interaction issues, and/or high pressurised water or gas, and/or, for CNS and HNS, Hydrogen – Deuterium at very low temperature and/or Graphite at high temperature. Such energetic experimental devices can initiate significant safety transients,
- Competition from operational point of view: the discussion is about the “multipurpose” characteristics of a multipurpose reactor. The challenge is to optimise a reactor from CAPEX and OPEX points of view at the same time for all subsets of priorities inside the above list of reactor applications. To be more precise, this is especially the case between neutron beam applications, radioisotope production and Material and Fuel testing.

In addition, during the design phase, the future utilization can only be anticipated: it is difficult to know what will be the needs of experimental programs for the next 60 or 80 years, what will be the needed radioisotopes in the future, what will be the needed activities and the other means of production for these radioisotopes, what will be the safety issues to be analysed at material and fuel level in support to future power plants, what will be the new fields for neutron beam applications and what will be the future safety requirements.

Table 4 §8 summarises the main features related to the various experimental devices in means of usual location of the experimental device, flux level or other requirements, volume related to one irradiation location, relative degrees of complexity for the licensing and safety process, relative level of constraint for reactor operation, relative level of future evolution for that kind of experiment.

Even if all these topics are challenging, nothing is totally irrelevant, thanks to all the feedback from the past projects and operations and the continuous increase of the efficiency of the methods, calculation schemes and computer performance.

As usual, the key point is the quality and the coherence between the project requirements.

3 Core & Reactor block types

A great variety of different core and reactor blocks designs have been built in the past for the ≈774 research reactors of the IAEA database.

This derives from choices made at design stage:
- Nature and layout of the experimental load: in-core devices, in-reflector devices,
- Layout of the core cooling, reflector and experimental load, with dedicated primary cooling circuits or common one,
- Flow direction of the primary cooling circuits (upward, downward, downward-upward),
- Type and location of the support structure: support grid, core rack, housing vessel,
- Number, type and location of the shutdown systems: above the core, under the core, solid, liquid…
- Type and layout of the reflector: Beryllium blocks, heavy water tank, light water, graphite, mix of different reflector types.

Paper <2> gives an overview of different types of reactors among the population of high performance research reactors:
- Open-core downward flow,
- Open-core upward flow,
- Tank-in-pool open primary circuit with pressure reference from the pool,
- Tank-in-pool with an enclosed leak tight primary circuit.

Based on these different reactor designs, 3 main types of core and reactor blocks are distinguished here in matter of primary circuit layout and housing vessel.

Type 1: The core, neutron source without in-core experimental devices, is surrounded by the housing vessel and the reflector where the whole experimental load is located. Generally, the core is small and in some cases with only one fuel assembly.
Examples: FRM-II, ORPHEE, RHF…
From a design point of view and the related compromise, it is a quite simple case. The lack of in-core experimental load allows

keeping the upper core plenum for the shutdown system.
The reflector is not inevitably a heavy water tank. Usually the priority is for Cold Neutron Source, Hot Neutron Source and neutron beams and the experimental load management objective consists of inserting the other devices at the relevant fluxes without perturbing the steadiness of the neutron beams.
With a heavy water tank reflector, the in-reflector shutdown system can be a mechanical system with fast actuation or an hydraulic system performing a tank draining with slower actuation (possible if safety requirements are not too stringent).

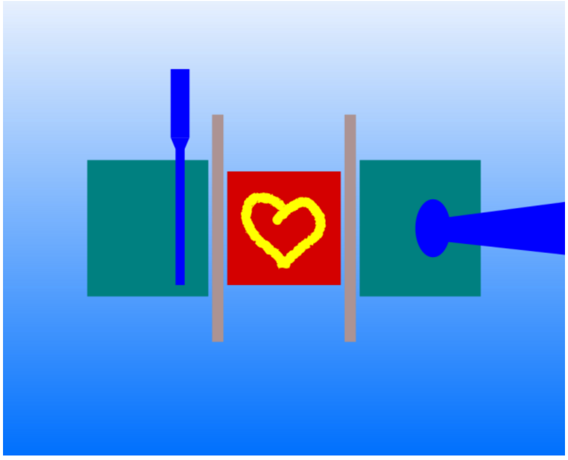

Figure 2: Core & Reactor Block Type 1

Type 2: The core, including in-core experimental devices, is surrounded by the housing vessel and the reflector, with ex-core experimental devices,
Examples: JHR, OSIRIS, ATR, CARR…
The experimental load is both in core and in reflector. This is typical to MTR with in-core material irradiation devices (for fast flux and high dpa) and in-reflector fuel irradiation devices.
The location of the housing vessel between the core and the reflector responds to 2 possible needs:

- Optimization of the pumping system (low total flowrate) in the cases of high power research reactor with a high core flowrate (upward or downward) and an adapted reflector flowrate (usually downward),
- The volume and distance reservation for the backward movement of up-to-date fuel ramping test devices (displacement system).

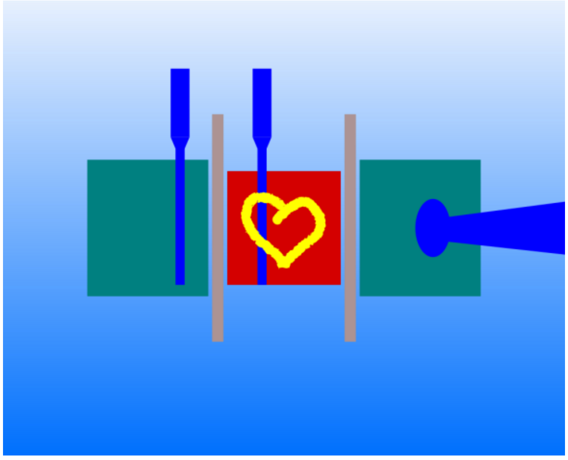

Figure 3: Core & Reactor Block Type 2

The experimental load is a key driver depending on the volume of the experimental load:

- In case of frequent loading and unloading of in-core devices, the usual choice is to locate the control rod drive mechanisms in a crypt under the reactor pool to preserve the core upper plenum for the experiment devices,
- The objective to optimize the flux level for the in-reflector experimental devices is in competition with a possible in-reflector shutdown system.

Type 3: The core and the reflector and the whole of the experimental load are surrounded by the same housing vessel.

Examples: BR2, LVR-15, BRR…
With both the core and the reflector inside the housing vessel, the reactor performances have the benefit of :

- A high flexibility of use for the location of the experimental load in the case of high flux performance reactor,
- An optimization of the in-reflector thermal flux for the low power and the medium power reactors with a better feeding of the reflector by the core. In that type, high thermal neutron fluxes are reachable.

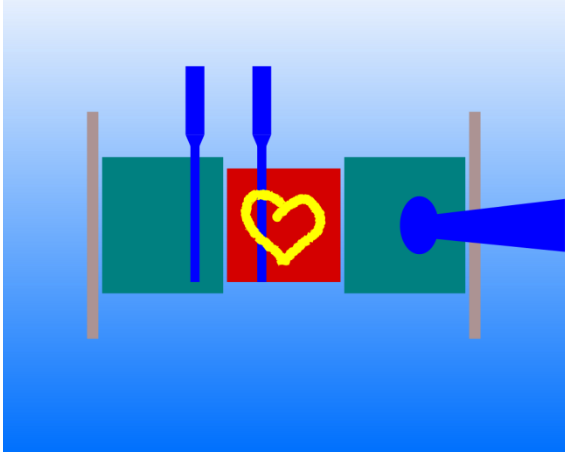

Figure 4: Core & Reactor Block Type 3

To be noted: a reactor is not systemically of type 1 or 2 or 3. For example, between the types 2 and 3: a reactor can be halfway between them (asymmetric housing vessel) or can move from one type to another one during its life because of the adaptation of its experimental load. This key-point hinges on well-fitted initial design and a good procurement phase. This point is more easily addressed with Beryllium reflectors.

4 Some insights concerning the design

A designer has to manage various design situations:

- Initial design of the whole or of a part of a research reactor,
- Modification for adaptability or safety purpose of an existing reactor, from its own design or not.

In any case, a good understanding of the pros and cons of various design options is of first interest regarding the various experimental loads:

- Overall layout of the core and reactor blocks, illustrated in §3 and related technological choices for the mechanical components,
- Layout of the primary cooling systems. For instance, paper <6> details solutions developed to optimise the JHR ex-core experimental load flexibility. JHR experimental load requirements led to an advanced design of the reflector especially for reflector beryllium blocks with heterogeneous gamma heating according to the presence of gamma shield which have been inserted for a high quality fuel tests. Taking into account the need to load and unload experimental devices while reactor is under operation, thermal-hydraulic design had to manage these cooling constraints whereas a downward flow cooling circuit limits the maximum mass flow and its head losses,
- Management strategy of the flow by-passes of the various heating surfaces (fuel assemblies, external surfaces of experimental loops or capsules, Molybdenum targets…) in relation with licensing, easiness of operation and adaptability,
- Overall compliance strategy in operation, related to the design and procurement phases and to the integration of fabrication tolerances, calculation scheme uncertainties and operation characteristics. Open discussions with other research reactor designers, such as between former AREVA NP GmbH and AREVA TA (now TechnicAtome), technical exchanges and R&D cooperation with fuel manufacturer, like Framatome-CERCA and internal and external exchanges with operators favour optimized Operational Limits and Conditions and CAPEX/OPEX optimisations,
- Measurements of the relevant parameters concerning safety and performances of the core and related command-control architecture and application of the graded approach,
- Structuring choices like fuel assembly characteristics and reflector material and shape,
- Technologies and layout of the shutdown systems.

To complement, one topic is now highlighted: reflector material choice.

The list of commonly used reflector material is quite short: beryllium, graphite, heavy water, light water. Table 2 presents an overview of the content of the 2016 IAEA RR database for the 99 operational reactors with power ≥ 1 MW and water coolant (H_2O or D_2O). In addition, this table indicates the split between the 2 reactor categories in the IAEA database: research and test. The heavy water is mainly used for physical research reactors with a network of neutron beams, in some cases with Cold Neutron Source (CNS) and less frequently Hot Neutron Source (HNS), see <9>. But there are also high performance physical research reactors with neutron beams and a beryllium reflector. The association between neutron beams and heavy water tank is not systematic even if recent examples are OPAL and FRM-II.

<table>
<tr><th></th><th colspan="2">Be</th><th colspan="2">Graphite</th><th colspan="2">Heavy Water</th><th colspan="2">Light Water</th></tr>
<tr><td rowspan="2">Be</td><td colspan="2">20</td><td colspan="2" rowspan="2"></td><td colspan="2" rowspan="2"></td><td colspan="2" rowspan="2"></td></tr>
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<tr><td rowspan="2">Heavy Water</td><td colspan="2">-</td><td colspan="2">5</td><td colspan="2">9</td><td colspan="2" rowspan="2"></td></tr>
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<tr><td rowspan="2">Light Water</td><td colspan="2">12</td><td colspan="2">11</td><td colspan="2">1</td><td colspan="2">7</td></tr>
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Table 2: Reflectors - Extract from 2016 IAEA RR database (reflector material and mix of 2 reflector materials) – First criticality between 1954 and 2004, P ≥ 1 MW, operational reactors
Legend: grey: number of reactors; yellow: number for category research; green: number for category test.
To be noted: mix of 3 reflector materials: Be-D2O-H2O: 2 reactors, C-Be-H2O: 2 reactors

Table 3, coherent with the analysis of <8>, makes a comparison between heavy water and beryllium for the main parameters, especially from experimental load point of view.

To comment and summarize Table 3, the choice between heavy water tank and the various layouts of Beryllium reflector is not obvious. Both solutions have pros and cons and it depends on the requirements of each project. Nevertheless:

- Heavy water reflector is the preferred solution if a large number of neutron beams (horizontal, vertical, inclined) and other experimental devices like radioisotope production, Si doping, Neutron Activation are required and if the future experimental load is sufficiently defined (core and reactor block types 1 and 2),
- Be reflector solution is the preferred solution in case of material tests requirements such as horizontal displacement system (core and reactor block types 1 and 2) and/or optimisation between high reflector neutron flux and low power and low CAPEX and OPEX (core and reactor block types 2 and 3) for the purpose of efficient radioisotope production, Neutron Activation Analysis and Si doping,
- From safety and licensing point of view, neither heavy water reflector nor Be reflector have a prohibitive impact. So, the choice lies on local situations,
- Mixed solution (for example, core with Be blocks and heavy water tank) are also possible but globally more complicated and less efficient.

Parameter	Heavy-water reflector	Beryllium reflector
Ex-core experimental devices: flexibility	D_2O tank cannot be easily modified after first irradiation. The replacement is a major refurbishment. Provisions for adaptability of the experimental load have to be addressed at initial design stage.	Be-reflector is modular. The Be-block can come along with its experimental device.
In-core experimental devices: flexibility	The D_2O-tank cannot easily contribute to the tuning of the reactivity in case of in-core experimental load adap-tation.	As a system, Be-reflector participates to the tuning of the core reactivity.
Flexibility - Core size adaptation (evolution of experimental load)	The inner diameter of the heavy water tank is fixed. The adaptation of the core shape needs to complement with another reflector material.	The number of Be-blocks and the layout of the Be-reflector can be easily adapted.
Thermal flux performances (see Figure 5)	The characteristics of the heavy water compensate the need of a structure between core and reflector and the related light-water gaps.	If a high level of flexibility is required, the Be-blocks are split and the Be lattice contains water gaps.
Decommissioning	After treatment, heavy water is reusable.	At current time, the Be is not retreated.
Radiation protection	Tritium surveillance and management is required.	No special issue.
CAPEX	More expensive than Be due to special heavy water circuits even if some D_2O treatment can be processed outside of the reactor.	See opposite
OPEX	Circuits operation and more tests during operation.	Be reflector blocks design life is more or less equivalent to the reactor design life. For high flux reactors, it is possible to reshuffle Be-blocks to extent their operating life.
Safety – Shutdown systems	2 main possibilities: Solid shutdown systems (fast actuation: second or a couple of seconds) Draining of the heavy water tank (slower actuation: a dozen or so of seconds, see <11>)	Solid shutdown system (fast actuation).
Safety – Management of reactivity feedback coefficient	The risk of positive feedback coefficient is related to thermomechanical effects. They have to be properly assessed from the beginning of the design.	The risk of positive feedback coefficient is related to the targeted reactivity efficiency (see <7>).
Core performance – Lifecycle (core reactivity point of view)	Heavy water is more efficient than light water and less efficient than Be-blocks and graphite (see figure 6). The poisoning of D_2O by H_2O (tank leakage) has to be managed and monitored	From reactivity point of view, the Be is more efficient than heavy water (see figure 6). With high thermal flux, neutron poisoning of the Be by He3 has to be assessed (for core operation after refuelling)

Table 3: Comparison between Heavy water and Beryllium reflector

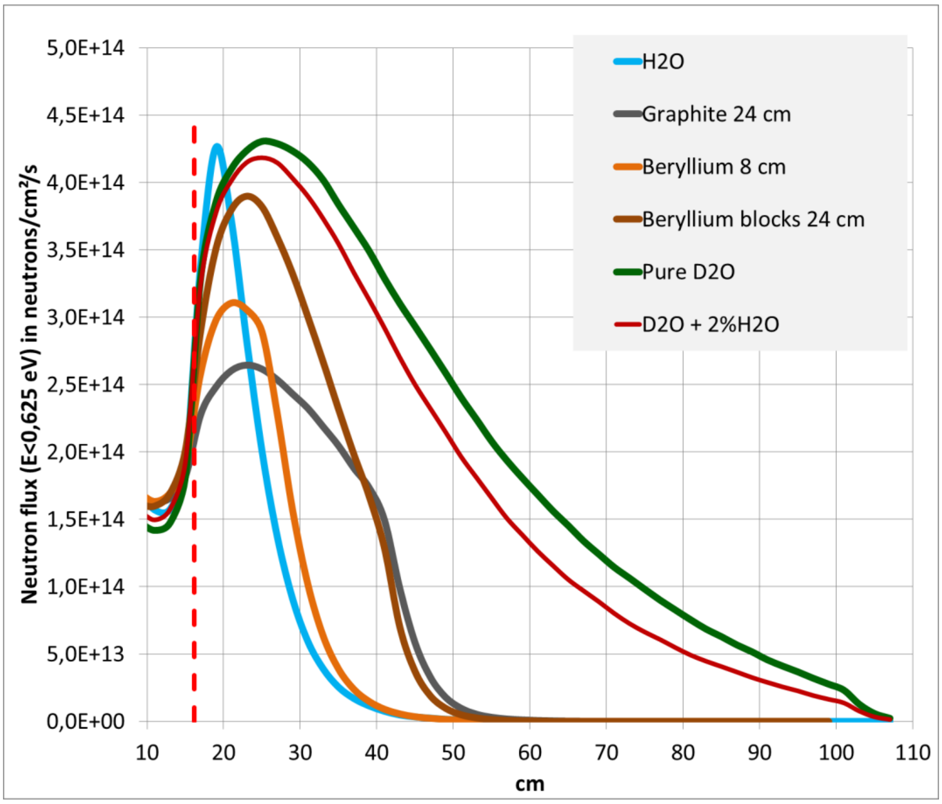

Figure 5: Thermal neutron flux reactivity - Comparison between pure D_2O, H_2O, fresh Be-block with water gaps and graphite

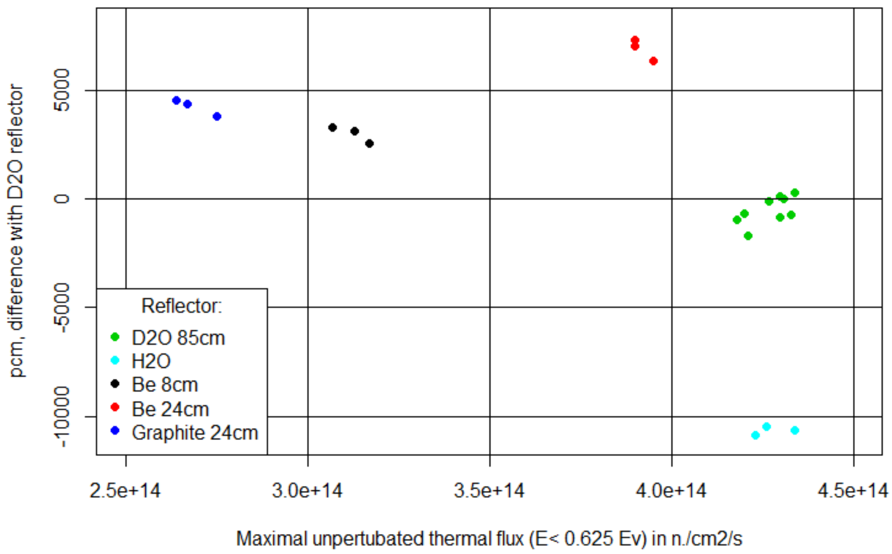

Figure 6: Core reactivity - Comparison between pure D2O, H2O, fresh Be-block with water gaps and graphite

5 Example of the safety/licensing approach for the JHR experimental devices

The safety approach applied to the implementation of experimental devices in a research reactor such as JHR is based on the following principle (see <10>):

- Firstly, the number of barriers to be considered for each experimental device in the core or the reflector is defined according to the safety objectives or criteria based

either technical or radiological requirements; these criteria can also be used to define the number of hanging or anti-blow-out systems,
- Secondly, the bounding conditions (known as PIEs) associated to the experimental devices (normal, incidental and accidental) are analysed in order to verify that the safety objectives or criteria are met; internal and external hazards are also analysed.

In practice, the approach consists in:
- Identifying the hazards from the experimental devices either in normal operating conditions and also in case of malfunction of the devices,
- Identifying the provisions (barriers, hanging or anti-blow-out systems) together with their failure to be considered,
- Implementation in the design and manufacturing of the provisions, in relation with the bounding conditions selected (e.g. PIEs resulting from the reactor, the experimental device itself or another experimental device),
- Verifying the adequacy of the provisions according to the hazards identified.

For JHR, each experimental device is classified according to the potential consequences (aggression and radiological) induced in case of failure without considering any provisions:
- Type A : experimental device which any failure do not challenge the operation of the facility or induces limited consequences comparable to Anticipated Operational Occurrence (AOO),
- Type L1: experimental device which any failure induces consequences comparable to DBC3/DBC4,
- Type L2: experimental device which any failure induces consequences more important than DBC3/DBC4 but still within the design of the facility (DEC-B).

According to this classification, the safety demonstration is based on the requirements applied to the experimental devices for different aspects such as:
- The confinement ensured by the barriers and their design (pressure hazard),
- The reactivity level in case of ejection (hanging or anti-blow-out systems),
- The reactivity control and efficiency of absorbers (reactivity variation),
- The cooling ensured by different systems (residual heat),
- The H_2 level,
- The seismic design.

Regarding the confinement, the number of barriers is defined as follows for each experimental device:

Experimental device type	**Technical criteria**	**Radiological criteria**	**Nb of barriers**
A	No consequences on: - Shutdown System - Cooling system	Radiological consequences comparable to AOO	0
L1	Limited impact on the core (partial core melt) No consequences on Shutdown System Heat removed in the long term	Radiological consequences comparable to DBC3/DBC4	1
L2	Serious consequences on core	Radiological consequences comparable to DEC-B	2

Operational Limits and Conditions are carried out to address the different hazards with the same graded approach. The main parameters are:

- Experimental device inner pressure,
- Experimental load maximum energy,
- In-core NaK device maximum energy,
- Maximum reactivity introduced in case of ejection of the experimental device,
- Maximum core reactivity variation (pcm/s),
- Maximum experimental load reactivity.

In conclusion, regarding the experimental devices implemented in the core and the reflector of the JHR reactor, all safety aspects have been analysed in order to demonstrate the safety.

As BORAX accident has been postulated at the beginning of the design and is considered as a severe accident condition in JHR reactor, all accidents conditions associated to the experimental devices turn out to be bounded by this accident. Finally, the application of requirements on experimental devices appears to be sufficient to meet the safety criteria and gives furthermore flexibility for the operability of the facility.

6 Conclusion

To conclude this brief overview of the experimental load-oriented design of the core and reactor block of the multipurpose reactors, the technical selection of the design is mainly driven by performance considerations. And this remains true for modifications of an existing reactor.

Three main types of core and reactor blocks and two main reflector materials (heavy water tank and Be blocks) are considered:

- Heavy water reflector is the preferred solution if a large number of neutron beams (horizontal, vertical, inclined) and other experimental devices like radioisotope production, Si doping, Neutron Activation are required and if the future experimental load is sufficiently defined (core and reactor block types 1 and 2),
- Be reflector solution is the preferred solution in case of material tests requirements such as horizontal displacement system (core and reactor block types 1 and 2) and/or optimization between high reflector neutron flux and low power and low CAPEX and OPEX (core and reactor block types 2 and 3) for the purpose of efficient radioisotope production, Neutron Activation Analysis and Si doping.

Depending on local situations, more subjective safety and/or licensing considerations can interact with the selection process and have, legitimately, to be addressed.

For the safety of the experimental load, this paper presents a synthesis of JHR approach to allow a high level of flexibility and adaptability for the whole reactor life. When the characteristics of the more stringent experimental devices are taken into account early in the design, the operator is facing no safety issues.

7 References

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8 Appendix

Main applications	Location[1]	Flux or other requirement[2]	Current additional requirement	Volume[3]	Licensing Safety[4]	Operation: Constraints[5]	Future[6]
Neutrons beams	R	$\approx 10^{6}$-10^{7}	Steadiness of the flux, Thermal/Fast ratio	4	1	1	1
Neutron beams with CNS	R		When CNS is off line, reactor can be on (for other experimental devices)	5	2	1-3	2
Neutron beam with HNS	R		-	4	1	1	1
Prompt Gamma Neutron Activation Analysis	R	10^{8}	Tangential beam tube		1	1	1
Radioisotope production: inert target	C, R	up to $\approx 5\ 10^{14}$	Loading and unloading at full power Minimal fast flux	1	1	1	1
Radioisotope production: fissile target	C, R	> 20 kW/target		3	2-3	2	2
Neutron doping transmutation	R	$5\ 10^{13}$	Homogeneity of the neutron flux Ingots size: 8”	5	1	1	1
Material testing : capsule - inert fluid	C, R	$\approx 5\ 10^{14}$	Definition of related neutronic models Thermal/Fast ratios, Neutron/gamma ratio, range of various neutron flux between different devices, local/core fission power	1-3	1	1	2-3
Material testing: capsule - active fluid	C, R			1-3	1-2	1-2	2-3
Material testing : loop	(C), R			4	2-3	2	2-3
Fuel testing : capsule	C, R	Up to $\approx$500 W/cm (1wt%U235)		1-2	1-2	1	2-3
Fuel testing: loop	(C), R			3	2-3	2	2-3
Fuel testing : loop on displacement system	R			5	2-3	3	2-3
Neutron Activation Analysis	R	> $5\ 10^{11}$	-	2	1	1	1

[1]: Usual location of the experimental device: core C and/or reflector R. (C) means “possible but not frequent”.
[2]: Flux or other requirements: the range of flux (unit: n./cm²/s; T for thermal, F for Fast) or the power of the fuel part of the device.
[3]: Volume related to one experimental device: 1: device size < MTR fuel assembly; 3: device size ≈ FA (around 80x80mm); 5: device size >> FA.
[4]: Relative degrees: 1 for a low level; 2 for medium one; 3 for a more stringent one.
[5]: Relative degrees: 1 for a low level; 2 for medium one; 3 for a more stringent one.
[6]: Relative level of future evolution for that kind of experimental device: 1: application and experimental device quite mature; 2: some improvements are likely in the future; 3: a lot of improvements are likely in the future due to increase of requirements and/or new needs.

Table 4: Characteristics of the main experimental devices