Contract Performance Demonstration Tests in the OPAL

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Abstract. This paper will describe the measurements and calculations that were done in the OPAL Reactor to demonstrate compliance against contractual Design Features and Performance Acceptance Criteria.
The contract specifies several neutronic aspects to be fulfilled by the core, the irradiation and the beam facilities design, which have to be verified during the commissioning tests. Guaranteed flux values will be taken as being for equilibrium core conditions. The relationship between values measured during commissioning (First Core) and the guaranteed values is largely based on calculations.

The calculated values are obtained modelling with full detail the measurement conditions using the INVAP traditional calculation lines: CITVAP and MCNP calculation lines.

1. Introduction

The OPAL Research reactor is a multi-purpose open-pool type reactor. The nominal fission power of the reactor is 20 MW. The core is located inside a chimney, surrounded by heavy water contained in the Reflector Vessel. The whole assembly is at the bottom of the Reactor Pool, which is full of de-mineralised light water acting as coolant and moderator and biological shielding.

The reactor has two operative neutron sources: a cold neutron source and a thermal neutron source, each of them feeding two tangential beams containing several supermirror neutron guide lines. The reactor also provides support for a third (hot) neutron source feeding one neutron beam tube.

The reflector vessel has also 17 vertical irradiation tubes, with 5 targets each, for bulk radioisotope production (Ir, Mo and I) and 19 pneumatic rigs with 57 multipurpose target positions: radioisotope production, neutron activation analysis (NAA), etc. Additionally, it also has 6 neutron transmutation Si doping (NTD) facilities.

2. Contract Requirements

The contract specifies several neutronic aspects to be fulfilled by the core, the irradiation and the beam facilities design, which have to be verified during the commissioning tests. The following list gives a summary of such warranted values:

2.1. Neutron Flux Level

- Several irradiation facilities require a minimum value for the neutron flux; but some of them require more strict flux control demanding a minimum and a maximum neutron flux value.

- Minimum flux levels are also specified for the cold and thermal beam facilities at the outlet of the different NG lines.

2.2. Neutron Spectra

There are different requirements on the flux spectra associated with:

- Cold Neutron Beam Facility: Maximum allowable peak in cold spectra

- Thermal Neutron Beam Facility: Maximum allowable peak in thermal spectra

- Radioisotope Production Facility: neutrons with energy lower than 0.6 eV

- Irradiation Facilities: Fast neutron flux (E>1.0 MeV)

2.3. Flux Homogeneity

There are requirements on the flux homogeneity on the different irradiation facilities, i.e. the axial homogeneity on NTD facilities, inside an irradiation can, and within several targets of the same flux level.

2.4. Flux Perturbation

There are strict requirements on the flux perturbation at the irradiation positions due to the movement of the irradiation samples.

There is also a requirement on the irradiation facilities flux perturbation during normal operation due to control rod movement.

Summarizing, all the facilities were designed taken into account a set of performance criteria related with the flux level, spectrum and perturbations.

3. Flux Measurement

Guaranteed flux values will be taken as being for equilibrium core conditions. The relationship between values measured during commissioning (First Core) and the guaranteed values is largely based on calculations.

The First core with 3 types of FA was specially designed to minimize the difference on the flux levels and distribution during the transition between the first core and the equilibrium core.

Measurements performed when equilibrium conditions have been more closely approximated will be performed where possible and considered necessary.

A time-of-flight instrument with a flight path greater than 1m was constructed to measure the Energy Spectrum. To account for possible variation of the energy spectra horizontally across the guide, measurements were performed at multiple spatial positions.

In the neutron guides, the thermal neutron flux value was measured using pure gold foils located at multiple spatial positions.

In the irradiation facilities, the thermal neutron flux was measured using diluted gold wires. Axial and radial flux profiles were measured in the Bulks Irradiation Facilities and Neutron Transmutation Doping (NTD) Facilities.

The Cadmium Ratio Method was used to obtain the absolute thermal flux values, reference [1].

The fast flux was measured in the NTD Facilities and Fast Flux Facilities using Nickel wires, reference [2].

The measured values are compared with the acceptance values and also with the calculated values.

The calculated values are obtained modelling with full detail the measurement conditions using the INVAP traditional calculation lines: CITVAP (reference [3]) and MCNP (reference [4]) calculation lines.

CITVAP code is used to follow the core burnup taking into account the operation conditions, (temperature and Control Plate positions). The CITVAP calculation line generates the Fuel Assembly numerical densities that will be required by the MCNP calculation line to model the measurement conditions.

The MCNP is used to obtain the calculated flux values in the irradiation facilities. The calculation model includes a full description of the irradiation conditions and core burnup.

4. Description of the Flux Measurement

4.1.*Bulks Irradiation Facilities (BIF)*

Diluted Gold wire activation detectors are placed in different positions within a BIF in order to determine the average thermal neutron flux per target region.

Only one irradiation per BIF is required to obtain the average thermal neutron flux per target region.

Several discrete Gold wires (about 8 mm length) are placed in a nylon chord to measure the flux in the axial direction. The 75 cm nylon chord is placed along the BIF axial direction.

The radial flux mapping is carried out using an Aluminium disc. From the radial mapping is obtained the Radial Factor.

The Average Thermal Neutron Flux per target region is obtained weighting the flux values measured in the axial direction with the Axial Weighting Factors and the Radial Factor.

4.2.*Silicon Irradiation Facilities*

Wire activation detectors are placed in different axial positions in the external cylindrical surface of the Silicon targets. Bare and under Cadmium diluted gold wires are used to measure the absolute thermal neutron flux and the thermal flux uniformity along the 600 mm of the Silicon target. In order to reduce the errors in the flux uniformity measurement, the axial flux profile is obtained as the average of two wires located at the same axial position.

Nickel wires are used to measure the fast neutron flux and obtain the thermal to fast flux ratio.

The radial uniformity is measured using thin Aluminium discs (1-2 mm thickness) that contain bare gold wires. Three Aluminium discs are used per NTD facility, one near the bottom of the target, one near the centre of the target and the last one near the top of the Silicon target.

At least 800 mm of undamaged Silicon ingots are loaded during the irradiation.

4.3.*Thermal Flux Pneumatic Conveyor Facilities*

Diluted Gold wire activation detectors are placed in different positions within a Can. Two irradiations per Pneumatic Facility are required to obtain the average thermal neutron flux. One irradiation using 3 diluted bare Gold wires and one irradiation using a diluted Gold wire under Cadmium.

The Average Thermal Neutron Flux per Pneumatic Facility is obtained weighting the measured flux values with the Axial Weighting Factors.

4.4.*Fast Flux Pneumatic Conveyor Facilities*

Nickel wire activation detectors are placed in different positions within a LRT Can. One irradiation using 3 Nickel wires per Pneumatic Facility is required to obtain the average fast neutron flux.

The Average Fast Neutron Flux per Pneumatic Facility is obtained weighting the measured flux values with the Axial Weighting Factors.

All the measured absolute flux values are extrapolated to 20 MW, according to the Power Calibration of the Nucleonic instrumentation.

5. Results

5.1.*Bulk Irradiation Facilities*

To describe the flux measurement methodology for bulks irradiation facilities, it is detailed the measuring of the average flux for the target 3 of the HF-1 irradiation facility.

To measure the radial flux profile, Gold wires are located in an Aluminium disc (Figure 1). Each wire located in the Aluminium disc has a weighting factor proportional to the area that surrounds the wire (Radial Weighting Factor).

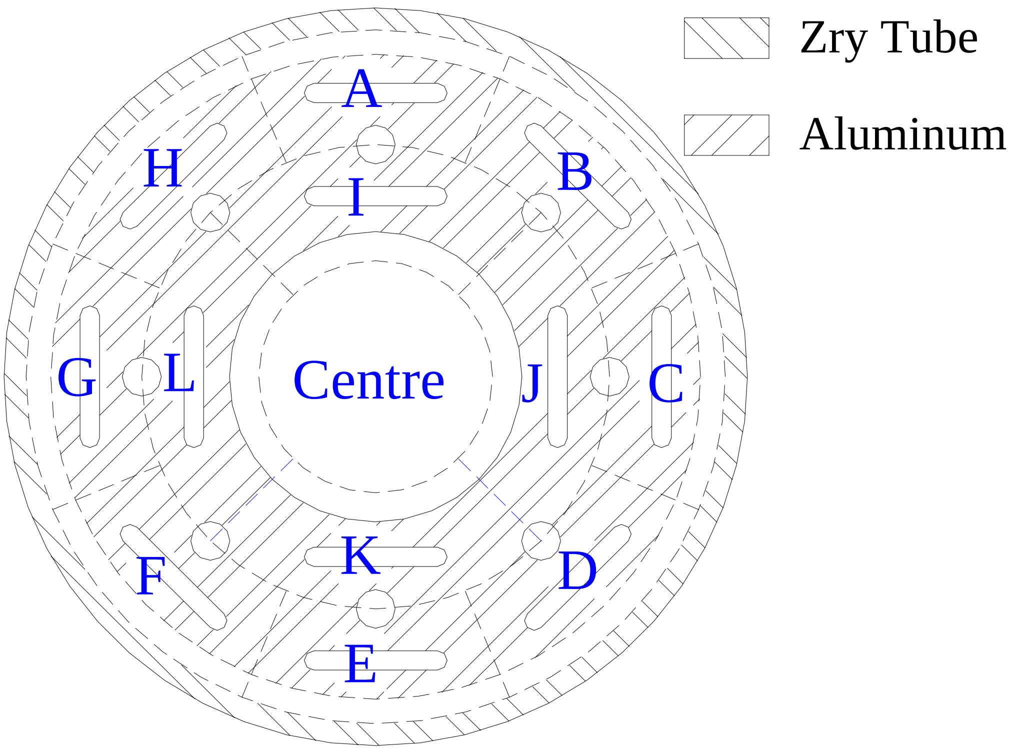

Figure 1: Location of the wires inside the Aluminium disc.

Radial Profile of BIF HF-1 at the axial position 0 cm				
Radial Position of the wire	Gold Wire [i]	Thermal Flux [n/cm^{2}s]	Radial Weighting Factor	Weighted Thermal Neutron Flux [n/cm^{2}s]
A	DG1901	1.14E+12	0.06903	7.88E+10
B	DG1902	1.20E+12	0.06903	8.26E+10
C	DG1903	1.28E+12	0.06903	8.83E+10
D	DG1904	1.44E+12	0.06903	9.92E+10
E	DG1905	1.47E+12	0.06903	1.01E+11
F	DG1906	1.41E+12	0.06903	9.76E+10
G	DG1907	1.33E+12	0.06903	9.21E+10
H	DG1908	1.19E+12	0.06903	8.23E+10
I	DG1909	1.23E+12	0.08395	1.04E+11
J	DG1910	1.31E+12	0.08395	1.10E+11
K	DG1911	1.36E+12	0.08395	1.14E+11
L	DG1912	1.33E+12	0.08395	1.11E+11
Centre	Interpolated	1.34E+12	0.11194	1.50E+11
SUM			1.00000	1.31E+12 (Average Radial Thermal Neutron Flux)

Table 1: Average Radial Thermal Neutron Flux Calculation

It is defined the Radial Factor as the Average Radial to Centre Flux Ratio.

Average Radial Thermal Neutron Flux [n/cm^{2}s]	1.31E+12
Thermal Neutron Flux at the Centre Position [n/cm^{2}s]	1.34E+12
Average Radial to Centre Flux Ratio (Radial Factor - RF).	0.9761

Table 2: Radial Factor Calculation

The radial factor is used to obtain the average flux in the target volume from the axial profile inside the target.

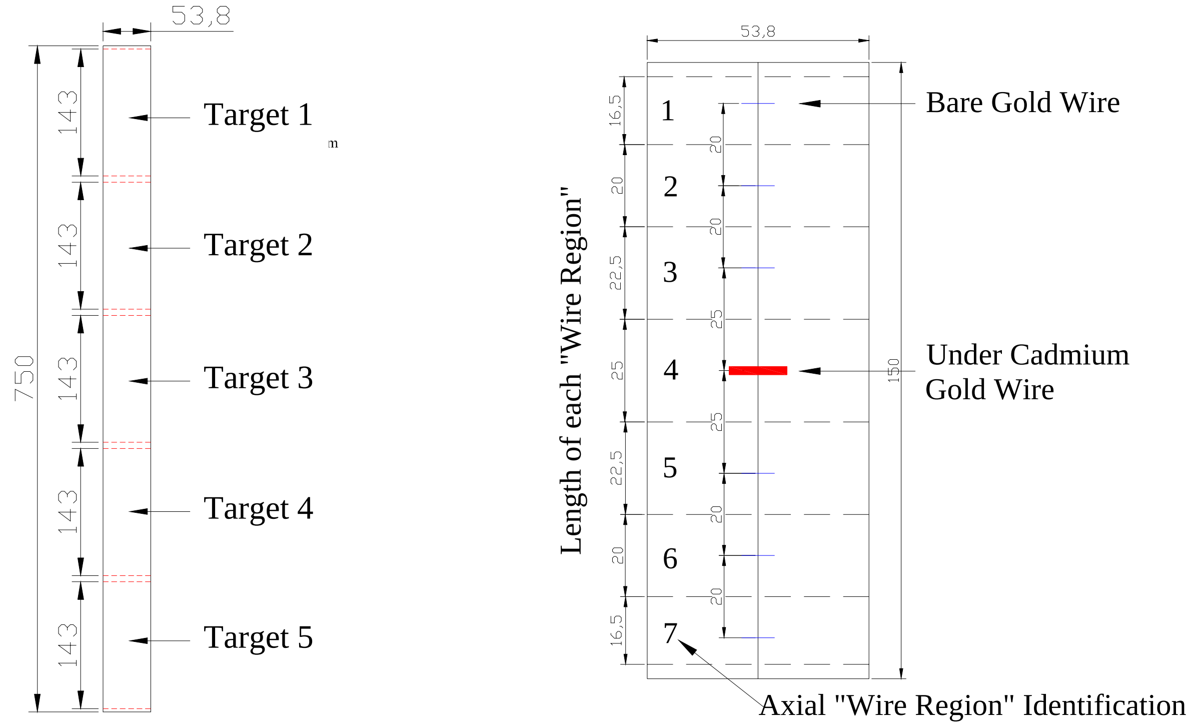

Figure 2: Location of the targets inside the BIF and location of the wire inside a target.

HF-1 Target 3						
Wire Region	Axial Position [cm]	Gold Wire [i]	Thermal Flux [n/cm^{2}s]	Axial Weighting Factor	Radial Factor	Weighted Thermal Neutron Flux [n/cm^{2}s]
1	6.5	DG1840	1.30E+12	0.11538	0.9761	1.47E+11
2	4.5	DG1841	1.37E+12	0.13986	0.9761	1.87E+11
3	2.5	DG1842	1.34E+12	0.15734	0.9761	2.06E+11
4	0.0	Interpolated	1.34E+12	0.17483	0.9761	2.29E+11
5	-2.5	DG1844	1.38E+12	0.15734	0.9761	2.13E+11
6	-4.5	DG1845	1.40E+12	0.13986	0.9761	1.91E+11
7	-6.5	DG1846	1.40E+12	0.11538	0.9761	1.58E+11
SUM				1.00000	--------	1.33E+12 (Average Thermal Neutron Flux)

Table 3: Average Thermal Neutron Flux Calculation in a BIF target.

Taking into account the reactor power during the Gold wire irradiation (102.3 kW), the thermal neutron flux for 20 MW reactor power is 2.60E+14

There are there types of Bulks Irradiation Facilities, according to the flux requirement:

- High Flux Irradiation Facilities: Designed to produce Ir^{192}.
- Medium Flux Irradiation Facilities: Designed to produce I^{131}.
- Low Flux Irradiation Facilities: Designed to produce Mo^{99}.

5.1.1. High Flux Irradiation Facilities

Requirements:

- Thermal Flux averaged within any target position: 1.4 E14 (min)
- Averaged Thermal Flux over all target positions: 2.0 E14 (min)

Up to date, the neutron flux was measured only in the HF-1. Table 4 shows the Thermal Neutron Flux in HF-1.

Facility		Thermal Neutron Flux [n/cm^{2}s]
HF-1	Target 1	1.43E+14
	Target 2	2.25E+14
	Target 3	2.60E+14
	Target 4	2.38E+14
	Target 5	1.43E+14
	Average	2.02E+14

Table 4: Thermal Neutron Flux in HF-1.

5.1.2. Medium Flux Irradiation Facilities

Requirements:

- Thermal Flux averaged within any target position: 9.4E13 (min)
- Averaged Thermal Flux over all target positions: 1.2 E14 (min)

Up to date, the neutron flux was measured in the MF-1 and MF-2. Due to the abnormal Control Rod Plate (CRP) configuration used during the irradiation of the gold wires, the flux value in the target 5 was reduced significantly. This measuring will be repeated for other CRP configuration. Table 5 shows the Thermal Neutron Flux in the Medium Flux Irradiation Facilities.

	Thermal Neutron Flux [n/cm^{2}s]	
	MF-1	MF-2
Target 1	1.02E+14	9.68E+13
Target 2	1.45E+14	1.55E+14
Target 3	1.71E+14	1.81E+14
Target 4	1.49E+14	1.58E+14
Target 5	8.62E+13	9.10E+13
Average	1.31E+14	1.36E+14

Table 5: Thermal Neutron Flux in the Medium Flux Irradiation Facilities

5.1.3. Low Flux Irradiation Facilities

Requirements:

- Thermal Flux averaged within any target position: 5.16E13 (min)

- Thermal Flux within any target position: 1.5E14 (max)
- Averaged Thermal Flux over all target positions: 8.0E13 (min)

Up to date, the neutron flux was measured in the LF-02, LF-08, LF-09 and LF-11. Table 6 shows the Thermal Neutron Flux in the Low Flux Irradiation Facilities.

	Thermal Neutron Flux [n/cm^{2}s]			
	LF-02	LF-08	LF-09	LF-11
Target 1	6.00E+13	6.61E+13	7.05E+13	6.21E+13
Target 2	9.42E+13	9.71E+13	1.01E+14	8.50E+13
Target 3	1.09E+14	1.10E+14	1.17E+14	1.05E+14
Target 4	1.03E+14	1.09E+14	1.16E+14	1.04E+14
Target 5	7.30E+13	7.14E+13	7.41E+13	7.44E+13
Average	8.78E+13	9.06E+13	9.55E+13	8.62E+13

Table 6: Thermal Neutron Flux in the Low Flux Irradiation Facilities

5.2. Silicon Irradiation Facilities

Requirements:

- Axial uniformity: +/- 5%
- Thermal to Fast flux ratio: 200 (min)

Up to date, the neutron flux was measured in the NTD-1, NTD-2, NTD-3 and NTD-6. Table 7 shows the Neutron Flux values in the Silicon Irradiation Facilities.

	Thermal Neutron Flux [n/cm^{2}s]		Thermal to Fast ratio		Uniformity (Wafers analysis)	
	Requirement	Measured Value	Requirement	Measured Value	Requirement	Measured Value
NTD-1	1.0E13 (+/- 20%)	8.32E+12	> 200	---	+/- 5%	+/- 2%
NTD-2	3.2E12 (+/- 20%)	2.69E+12	> 200	2764	+/- 5%	---
NTD-3	1.9E13 (+/- 30%)	1.44E+13	> 200	---	+/- 5%	+/- 5%
NTD-6	3.5E12 (+/- 20%)	2.91E+12	> 200	---	+/- 5%	---

Table 7: Neutron Flux values in the Silicon Irradiation Facilities.

5.3. Neutron Beams Facilities

In all cases measured so far the absolute flux exceeds the guarantee value.

- Performance of the thermal beam lines exceeds the Principal’s Limiting Acceptance Level of Performance and the Contractor’s Guaranteed Level of Performance in respect of beam lines TG3 and TG4. Although gold foil measurements have been performed on TG1, the spectrum has not yet been satisfactorily completed.

- Performance of the cold beam lines exceeds the Principal’s Limiting Acceptance Level of Performance in respect of beam lines CG3 and CG4. Neither gold foil measurements nor spectrum measurements have been performed on CG1 in the neutron guide hall.

- With exception of CG3 at the reactor face, performance of the cold beam lines exceeds the Contractor's Guaranteed Level of Performance in respect of beam lines CG3 and CG4.

- Beam uniformity is as expected in all instrument locations measured so far, given the source shapes and the neutron guide characteristics. This result is quite acceptable for intended neutron applications.

Further spectrum and spatial distribution measurements on the cold neutron beams are required to fully characterize the cold neutron source, and will be the subject of work planned to commence soon.

6. Conclusions

The neutron flux values measured in the Bulk Irradiation Facilities are in accordance with the values expected by calculation.

The measured flux values in the NTD facilities showed that:

- The absolute flux values fulfil the flux requirements.

- The flux uniformity along the 600 mm of Silicon target are in accordance with the calculated values, showing the proper design of the flux flattener at each facility.

- The thermal to fast flux ratio also fulfil the requirements, minimizing the damage in the Silicon single crystals.

The measurements performed in the Neutron Beams Facilities show that:

- In all cases the absolute flux exceeds the guarantee value.

- Beam uniformity is as expected in all instrument locations.

7. References

[1]. E262-97 **Standard Test Method for Determining Thermal Neutron Reaction and Fluence Rates by Radioactivation Techniques**.

[2]. E264-02 **Standard Test Method for Measuring Fast-Neutron Reaction Rates by Radioactivation of Nickel**.

[3]. Eduardo Villarino and Carlos Lecot, **Neutronic calculation code CITVAP 3.1**. IX Encontro Nacional de Fisica de reatores e Termo-hidrualica. Caxambu. Brasil. October 1993.

[4]. Briesmeister, J. F., Ed., **MCNP - A General Monte Carlo N-Particle Transport Code, Version 4C,** LA13709-M, Los Alamos National Laboratory (April 2000).