OPAL Cold Neutron Source Moderator Performance

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Abstract. The OPAL reactor at ANSTO has a cold neutron source (CNS) that operates for over 300 days a year with near 100% reliability, providing cold neutron beams to eight neutron scattering instruments. The high performance of the OPAL CNS is primarily due to its single phase liquid deuterium moderator, cooled by cryogenic helium and maintained by a vertical thermosiphon. In this paper, we present computational and experimental characterisation of the LD2 moderator including sensitivities of CNS heat load and flux on moderator temperature and reactor plant conditions such as core configuration, control rod movement and heavy water purity.

1. Introduction

The OPAL reactor is a 20 MW open pool reactor designed to be a world class source of neutrons [1]. The core is of compact design with 16 fuel assemblies and 5 control rods. There are no experimental facilities within the core. All the facilities are within a heavy water reflector vessel that surrounds to core (see FIG 1). The main applications for neutrons produced are production of radioisotopes for medical, industrial and research applications, irradiation of silicon ingots for neutron transmutation doping and neutron beams (both thermal and cold) for neutron scattering research in the Australian Centre for Neutron Scattering (ACNS) [2]. Cold neutrons are provided by a Cold Neutron Source (CNS) located 50 cm from the centre of the core.

The OPAL CNS is a cryogenically cooled moderator system that provides 20 liters of sub-cooled liquid deuterium (LD2) at 24 K in a cylindrical chamber installed in the reactor heavy water reflector [3]. The location of the CNS is near the peak of uppertubed thermal neutron flux. Neutrons entering the LD2 volume are moderated to low energies (<10 meV), corresponding to the temperature of the moderator around 24 K. Two neutron beams transport cold neutrons from the CNS to eight instruments installed along neutron guide systems.

At the beginning of 2017, it was reported by ACNS scientists that cold neutron flux has dropped markedly by some 20% at some instruments. Between the CNS and the instruments there are the beam tube, the In-Pile plug and primary shutter with neutron guide and in particular tens of meters of curved neutron guide, any of which could affect the neutron flux if some kind of deteriaration or fault has developed, as happened before [4]. It was therefore intially suspected that root cause was in the neutron guide system. But in a more detailed investigation that followed, we have identified the root cause.

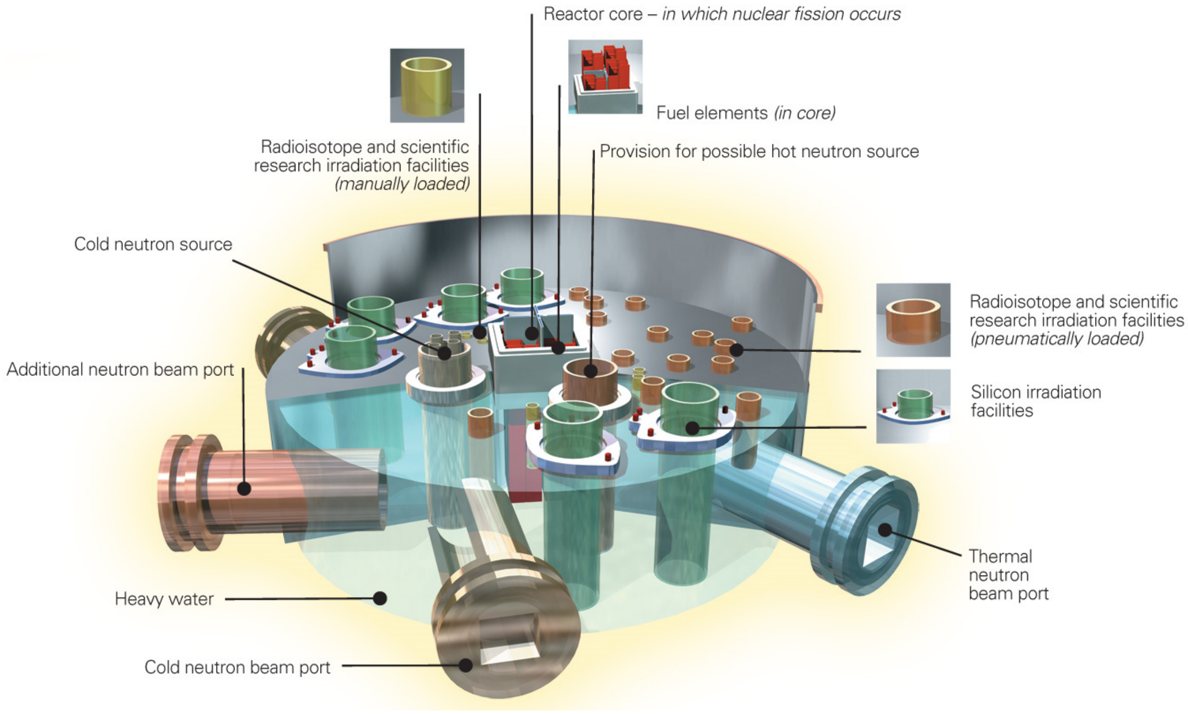

FIG 1. A 3D illustration of the OPAL reactor facilities layout

2. CNS Flux and Heat load

The neutron flux in the CNS is not directly measured. However, the CNS nuclear heat load, which is proportional to the neutron flux in the CNS, is accurately meaured and monitored by thermal balance in the helium cooling system. Based on thermal balance measurements taken in 2007 [5], we normalise the nuclear component of the heat load to 100% corresponding to 20 MW of reactor power. In FIG 1, we plot the CNS nuclear heat load together with the reactor power which is also normalised to 20 MW. It was then clear that for 18 months since the beginning of 2015, the heat load trend was tracking the reactor power very well, which varied between 19.5 MW and 20 MW most of the time. Significant deviations, both positive and negative, have become prominent since late 2016 until the present time, resembling a pattern of oscillation with a period of several monthly reactor cycles. The magnitude of the oscillation, from peak to trough, was about 20% from late 2016 to early 2017 and in excess of 25% during 2017. This is consistent with the 20% “flux drop” observed at the neutron instrumens. Furthermore, it is observed that the deviation was mostly constant within each reactor cycle but can change significantly from cycle to cycle Therefore, it seems most likely that the root cause lies in the variation of the CNS flux itself, rather than the neutron transport system. To find the root cause, we need to fully understand the CNS flux’s sensitivity to a whole range of relevant process and environemental conditions.

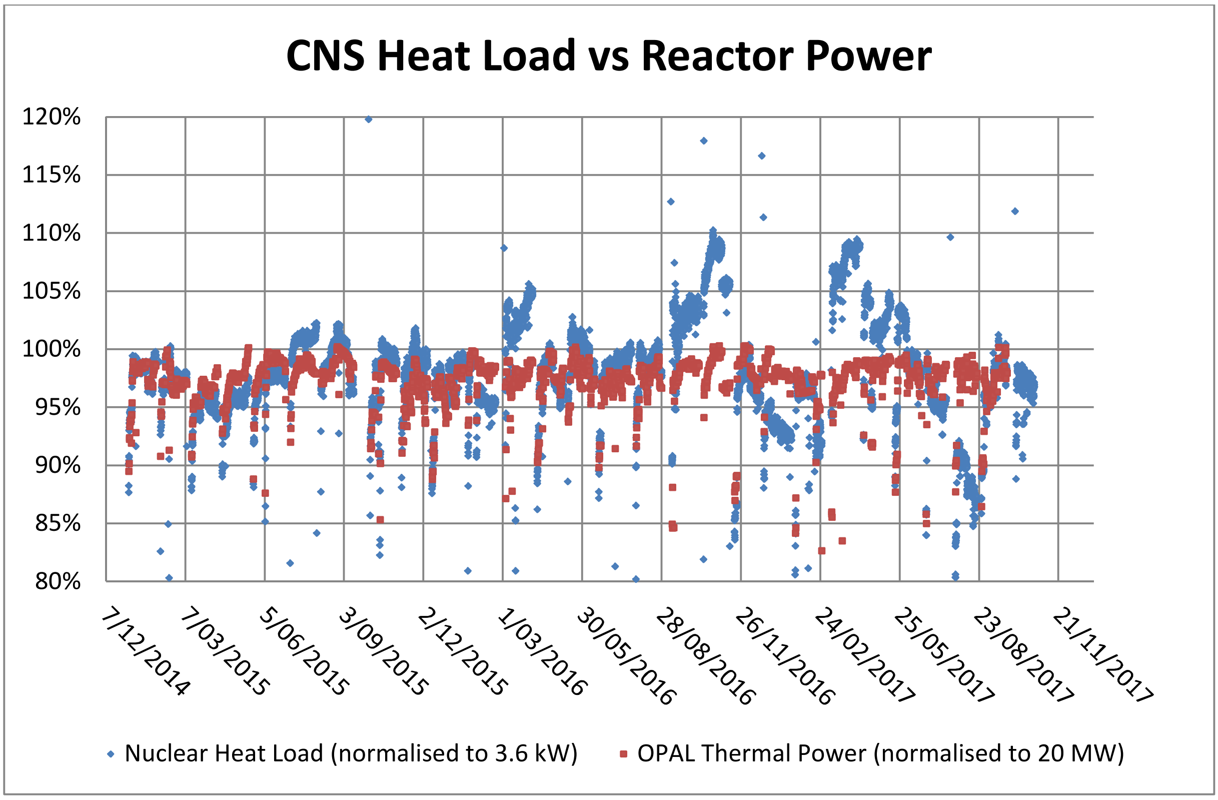

FIG 2. Long term operating trend of the CNS nuclear heat load and OPAL reactor thermal power. The resolution of each point is two hours for CNS heat load and six hours for reactor power.

3. CNS Flux Sensitivity

To fully understand the sensitivity to the process and environmental conditions, a parametric study has been performed using MCNP simulations. The figure of merit is the cold neutron flux at the reactor face. The relevant process prarameters have been chosen based on experience. We concentrate on three main areas: reactor core configuration including the control rods, reflector heavy water and CNS LD2 moderator. There is no evidence to suggest any of those parameters fluctuates wildly during routine operation. Nevertheless, it is important to assess just how sensitive the CNS flux is to those parameters. The results are summarised in TABLE I below.

The sensitivity analysis suggests that none of the heavy water and LD2 conditions could count for the observed 20%+ variation. For the control rods, although they can make a noticeable in-cycle difference, their movement is repeated each and every cycle, so they cannot account for the cycle to cycle drift. The same can be said for uranium target loading for Mo-99 production. From previous analysis, we know that when all the Mo-99 facilities are fully loaded, it can increase the CNS heat load by some 7%. However, uranium target loading and unloading is not only carried out frequently within each reactor cycle, but also repeated from cycle to cycle. So it cannot account for the cycle to cycle drift either.

That leaves the reactor core as the last possible explanation assessed thus far. Because the OPAL reactor fuel is managed by a five-subcycle strategy, it may just be conceivable that the 20%+ drift was accumulated by multiple cycles. Moreover, the cyclical nature of the fuel management strategy seems to correlate with the oscillatory pattern of the CNS flux deviation from the reactor power.

TABLE I: CNS flux sensitivity to process conditions based on MCNP calculations.

Process Conditions (nominal)	**Sensitivity**	**Typical Operational Variation by Conservative Estimation**	**Resultant CNS Flux Variation**
Heavy water purity (99.5%)	6.66%/%	±0.5%	±3.33%
Heavy water temperature (35 °C)	-0.0228%/°C	±1 °C	±0.0228%
Heavy water gap between CNS thimble and beam tube front face (1 mm)	-5.52%/mm	negligible	N/A
LD2 temperature (24.5 K)	-4.38%/K	±0.5 K	±2.2%
LD2 ortho/para ratio (3:1)	0.288%/%	Unknown but expected to be small	±1% (order of magnitude estimation)
Control rod positions (critical positions for the first core)	5.58% between actual configuration and that after 180° rotation	Control rod movement pattern is repeated in every reactor cycle	N/A
Reactor core (first core and equilibrium core)	4.56% between the two cores	Fuel management strategy	To be assessed further

4. Rector Core Flux Tilt

We use a diffusion code CITVAP 3.5 for OPAL reactor fuel management [6]. CITVAP is part of neutronic simulation programs developed by INVAP S.E. [7], which is an extensively modified and enhanced version of the diffusion theory code CITATION [8]. CITVAP makes use of cross-sections generated by the cell code CONDOR. CONDOR applies collision probabilities methods to a 1D or 2D model of one reactor component, e.g., fuel assembly or part of a control rod. CITVAP models the entire core and reflector vessel including the irradiation facilities.

The root cause of the CNS heat load deviation from reactor power was finally revealed when we used CITVAP to check the power distribution in the core. We discovered a “flux tilt”, which is based on the average fuel assemblies’ relative power distribution for the rows 1 and 2 in the core arrangement shown below. We produced a cycle-average flux tilt parameter and trended it over many reactor cycles. When the flux tilt trend is overlaid on FIG. 2, as shown in FIG. 4, we see a very strong correlation with the CNS heat load deviation. What this means is that the configuration of the fuel assemblies impacts the power distribution in the core, resulting in the neutron flux in the refelctor vessel (such as at the position of the

CNS) to fluctuate significantly over periods of several reactor cycles, deviating from its historical average by more than 10% positively as well negatively. Although fluctuation of this magnitude can be easily absorbed by the margin in the CNS refrigeration cooling system such that the LD2 moderator remains in liquid phase comfortably, it is not ideal for the neutron instruments, with some experiments enjoying 20% more flux than others.

As to why the fuel management strategy has changed since 2016 will not be discussed here, suffice to say that it can be explained by actual events.

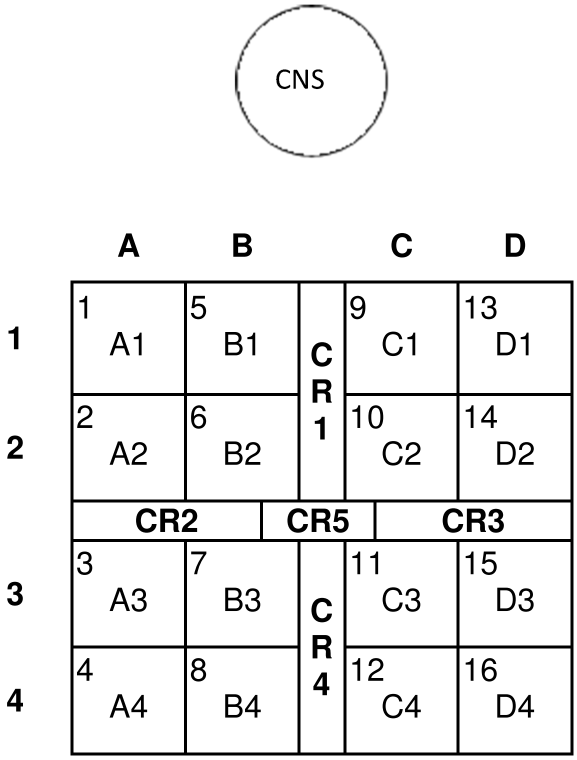

FIG 3. A schematic showing the relative position of OPAL reactor core and CNS in its north. There are16 FAs in a 4×4 matrix in the core and 5 control rods in between the quadrants.

5. Conclusions

We have shown that the neutron flux in the OPAL reactor CNS, as indirectly measured by the CNS nuclear heat load, is sensitive to the fission power distribution in the reactor core. The current fuel management strategy causes spacial changes in the power disbution in the core that results in CNS flux variation of over 10% in both positive and negative directions.

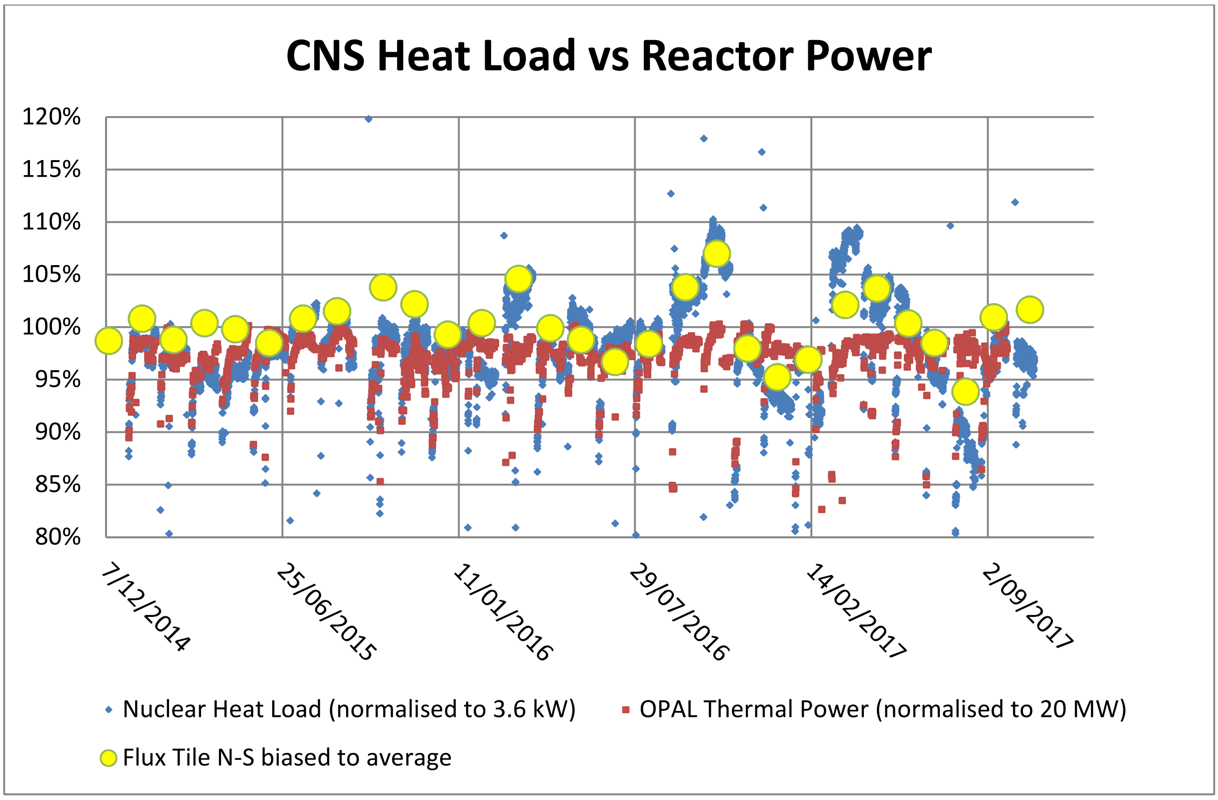

FIG 4. FIG 2 overlaid by flux tilt trend

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