The OPAL Cold Neutron Source Heat Load Measurements

Weijian Lu[*] and Russell Thiering

Australian Nuclear Science and Technology Organisation
Lucas Heights, NSW 2234, Australia

ABSTRACT

Australia's first Cold Neutron Source (CNS) is a key component of the OPAL (Open Pool Australian Light-water) Reactor's nuclear research program. It was designed to be a 20-litre single phase liquid deuterium source located in the heavy water reflector and able to deliver a cold flux of 1.4×10^{10} n/cm^2·s at the reactor face. The OPAL CNS was commissioned in early 2007 and has since been in operation under full reactor power. During that time the heat load and the thermohydraulic performance have been characterised. It has been demonstrated that all aspects of the thermohydraulic design specifications have been fulfilled.

1   Introduction

The OPAL Reactor is a 20 MW multi-purpose research reactor designed and constructed by INVAP and operated by the Australian Nuclear Science and Technology Organisation [1, 2]. It was commissioned for full power operation at the end of 2006. It uses MTR-type LEU fuel in a 16-fuel-assembly core, which is moderated and cooled by light water. Surrounding the core is a reflector vessel containing heavy water. All the irradiation facilities are located in the heavy water reflector, including the CNS.

The CNS is a key research facility on the OPAL Reactor [3, 4]. It provides cold neutrons (< 10 meV) through two tangential neutron beams and neutron guides downstream to serve neutron scattering experiments [5]. The CNS In-Pile is housed in a cylindrical and vertical vacuum containment, structurally part of the reflector vessel. The In-Pile consists of a two-leg thermosiphon with a cryogenic heat exchanger at the top in the cold leg and a moderator chamber at the bottom containing 20 litres of liquid deuterium, and a heavy water plug above the moderator chamber to minimise the loss of cold neutrons scattered upwards. A schematic presentation of the In-Pile thermosiphon with transfer paths is shown in Figure 1.

In Normal Operation (NO) mode, liquid deuterium is maintained in single phase by natural circulation, where heat is removed by cryogenic helium gas flowing through the heat exchanger as well as the jacket around the double-walled moderator chamber and the pipelines. The CNS can also run in Stand-by Operation (SO) mode, where room temperature helium is circulated through the In-Pile to provide adequate cooling at full reactor power. The SO mode significantly enhances the reactor's availability when the CNS is not fully functional or not required. In fact, this very design feature

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[*] Email: WJL@ansto.gov.au

has allowed the OPAL Reactor to be commissioned at full power in 2006 with an in-situ In-Pile without a fully functional cryogenic system.

Critical to the design and understanding of the CNS was the heat load on the In-Pile because it placed the most fundamental specification on the cryogenic system, the refrigeration power. The refrigeration power specification for the OPAL CNS cryogenic system was 5 kW.

At reactor power, the total heat load consists of two components: nuclear and non-nuclear. The nuclear heat load is due to neutron and gamma radiation. The non-nuclear heat load is due to thermal loss (thermal radiation, conduction and convection). In this study, for practical reasons, we group all the components that are proportional to the reactor power as nuclear heat load and the rest as non-nuclear heat load even though some components (e.g. core decay heat) are nuclear in nature. The heat load can be directly measured by performing a steady state thermal balance on the helium flow. That is, at steady state, the heat load Q on the In-Pile is

$$Q = c_p \cdot f \cdot (T_{out} - T_{in}),$$

where $c_p = 5.3 \, J/K \cdot g$ is helium's specific heat within the operational range, i.e. at temperatures between 20 K and 30 K and under pressures between 150 kPa and 300 kPa, f is the helium flow rate, and T_{in} and T_{out} are the helium In-Pile inlet and outlet temperatures, respectively. f, T_{in} and T_{out} are directly measured in the cryogenic system, so Q can be readily obtained.

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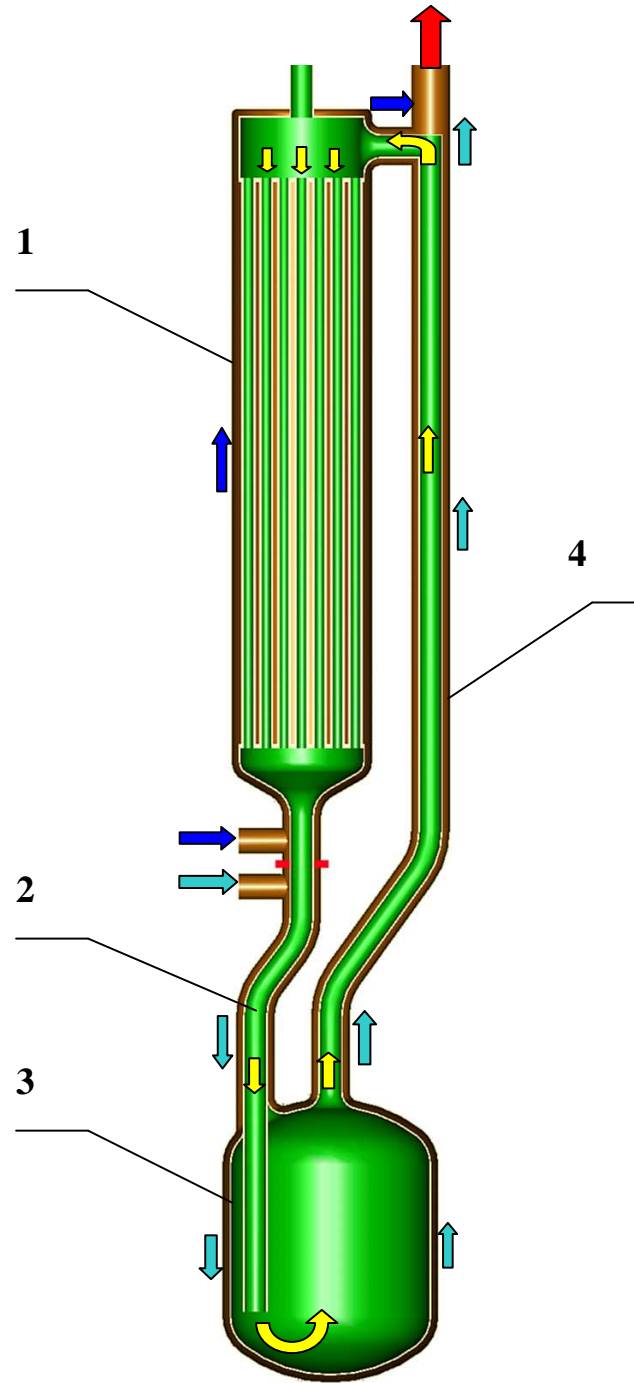
→ liquid deuterium flow

→ cold helium flow through the Heat Exchanger

→ cold helium flow through the Moderator Chamber

→ helium flow to the refrigerator

1 - shell and tube counter flow heat exchanger,
2 - tube-in-tube parallel flow heat exchanger as a downwards tube,
3 - moderator chamber,
4 - tube-in-tube parallel flow heat exchanger as an upwards tube.

Figure 1

2 Measurements of Heat Load

Before undertaking the In-Pile heat load measurements, we checked the accuracy of the instruments involved. While the flow meter has an acceptable accuracy (error < 1%), a noticeable bias was observed in the silicon temperature sensors. In a set of measurements performed at constant reactor power where we varied the helium flow, we identified a bias of 0.143 K in ΔT, i.e. $T_{out} - T_{in}$ (see Figure 2). This bias is corrected for all future measurements.

A series of thermal balance measurements at incremental reactor power levels were performed with results shown in Figure 3. We were able to separate the nuclear and non-nuclear components from those measurements. The slope of the linear fit to the data points gives the nuclear heat load in the unit of W/MW, and the y-axis intercept is the non-nuclear heat load in watts. Furthermore, by performing two sets of measurements, one with liquid deuterium (helium inlet temperature 20 K) and the other without liquid deuterium (helium inlet temperature 35 K), we could also separate the liquid deuterium heat load from the structural material heat load. The results are summarised in Table 1. At full reactor power of 20 MW, the total heat load on the CNS In-Pile is 4.0 kW under the measurement conditions.

Note that the non-nuclear heat load due to thermal loss not only includes the In-Pile but also the cryopipes between the inlet and outlet temperature sensors which are located outside the reactor pool. Correction due to the temperature sensors' bias, identified previously, is applied to the measurements. But such corrections mainly affect the non-nuclear heat load, because the bias is already largely eliminated from the slope of the linear fit.

During the design phase, Monte Carlo calculations by MCNP have estimated the total nuclear heat load to be 4.3 kW with a conservative margin [2]. Despite the fact that the liquid deuterium heat load was under-estimated (by about 30%) and the structural material heat load was over-estimated (by about 34%), the total estimate has come quite close to that measured. The estimate for the thermal loss (thermal radiation, conduction and convection) was theoretically estimated to be about 350 W, in acceptable agreement with the measured non-nuclear head load.

Several operation conditions can affect the In-Pile heat load, including the liquid deuterium temperature (determined by helium temperature and flow rate), core local power density (on the side closest to the CNS), control rod positions and neighbouring irradiation facilities. The effect of the liquid deuterium temperature will be discussed in more detail later in this report. Trending of the heat load over the last 8 reactor fuel cycles shows that the overall variation is no more than ±5%, which is minor and adequately covered by engineering margin.
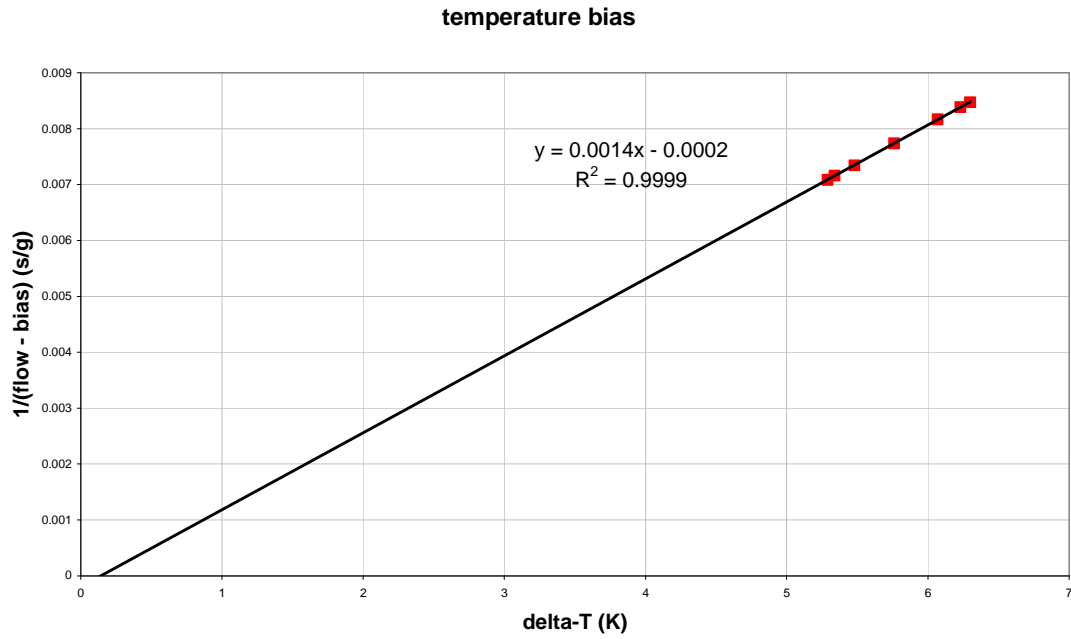
temperature bias

$$y = 0.0014x - 0.0002$$
$$R^2 = 0.9999$$

Figure 2 ΔT measured as a function of helium flow at constant reactor power

Table 1 Measured Heat Load on OPAL CNS

	Nuclear Heat Load (W/MW)	Non-nuclear Heat Load (W)
Total heat load at reactor power (linear fit through increasing power level, liquid deuterium, helium inlet temperature 20 K)	180.5	388
Structural material heat load at reactor power (linear fit through increasing power levels, gas deuterium, helium inlet temperature 35 K)	85.7	363
Liquid deuterium heat load at reactor power (difference between the total heat load and the structural material heat load)	94.8	n/a

Measured Heat Load on the CNS In-pile by Cryogenic Helium Thermal Balance
Linear fits indicate nuclear heat load (W/MW) by the slope and non-nuclear heat load by the offset (W)

$y = 180.49x + 387.57$
$R^2 = 0.9999$

$y = 85.666x + 363.1$
$R^2 = 0.9988$

- Liquid Deuterium
- Gas Deuterium
- Linear (Gas Deuterium)
- Linear (Liquid Deuterium)
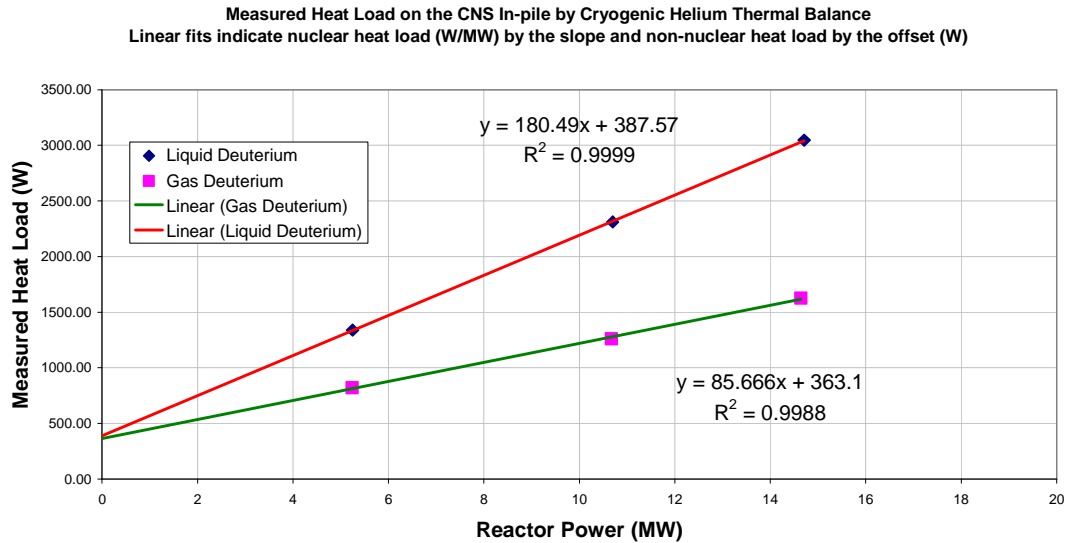
Measured Heat Load (W) — Reactor Power (MW)

Figure 3

3 Experimental Verification of Single Phase Liquid Deuterium

The OPAL CNS In-Pile thermosiphon was designed to operate with single phase and sub-cooled liquid deuterium. Liquid deuterium in the moderator chamber heats up under nuclear radiation and rises through the hot leg. The heat is primarily removed by helium through the cryogenic heat exchanger. Additional cooling is provided by helium flowing through the jacket around the double-walled moderator chamber and all the pipelines around the thermosiphon. The coldest point in liquid deuterium around the thermosiphon is at the inlet of the moderator, and the hottest point at the outlet, indicating uneven temperature distribution within the moderator chamber.

Two system parameters were measured as a function of helium temperature to verify that the liquid deuterium is in single phase, the liquid deuterium heat load (Figure 4) and liquid deuterium mass (Figure 5). Threshold behaviour is clearly observed from the trends of both parameters. They start to drop sharply at a helium outlet temperature of about 28.5 K, a clear sign of saturation, i.e. boiling.

The sensitivity of the liquid deuterium density under the operating condition is approximately -2%/K. The increase in the liquid deuterium heat load and mass is primarily due to its increasing density at lowered temperatures. Between the two system parameters, the heat load is a better indicator of the *average temperature* in the moderator chamber, thus the degree of cold neutron moderation, while the liquid deuterium mass is more closely related to the thermosiphon loop performance. The average temperature is a characteristic temperature we define as follows. At the saturation point identified in Figure 4, we assume the liquid deuterium is uniformly at saturation in the moderator chamber ($\rho = 0.15$ g/ml). We further assume the change

in liquid deuterium heat load is entirely due to the change in its average density in the moderator chamber. The average temperature is then the temperature at which the liquid deuterium density is equal to the average density.

As such, the average temperature corresponding to the first point in Figures 4 is 23.3 K. Therefore, the design aim of a ~ 23 K liquid deuterium moderator has been successfully achieved. This first point is also the coldest operating point on the OPAL CNS with a helium inlet temperature of 19.5 K.
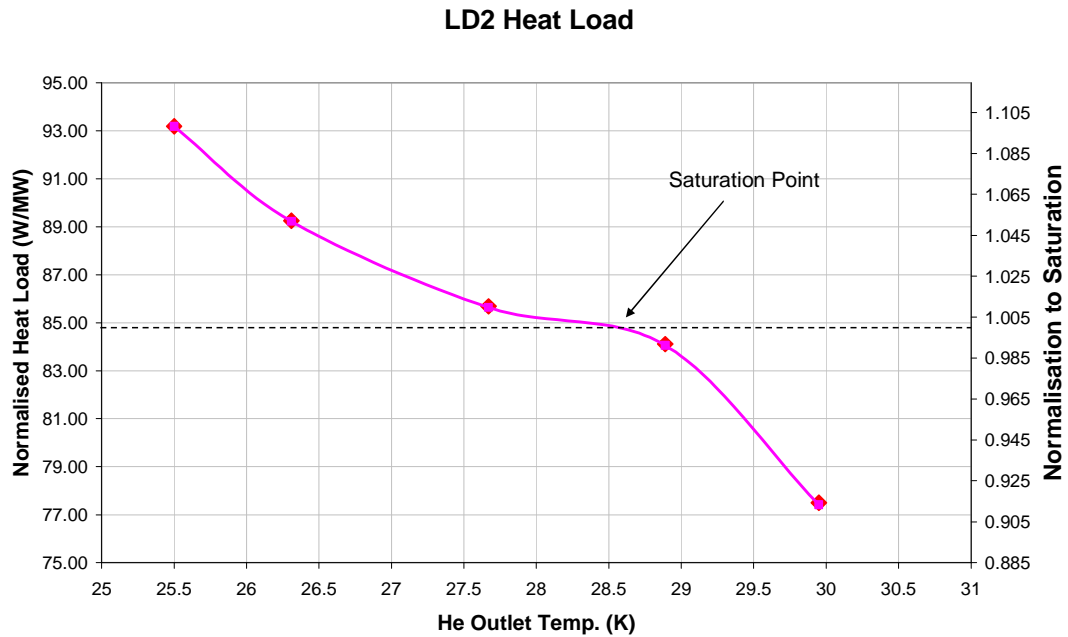
LD2 Heat Load

Figure 4 Liquid deuterium heat load measured as a function of helium gas temperature. The saturation point, i.e. the onset of the drop-off at ~ 28.5 K, is chosen as the mid-point between the 3rd and 4th points. Heat loads are normalised to the value at saturation point and shown on the secondary y-axis.
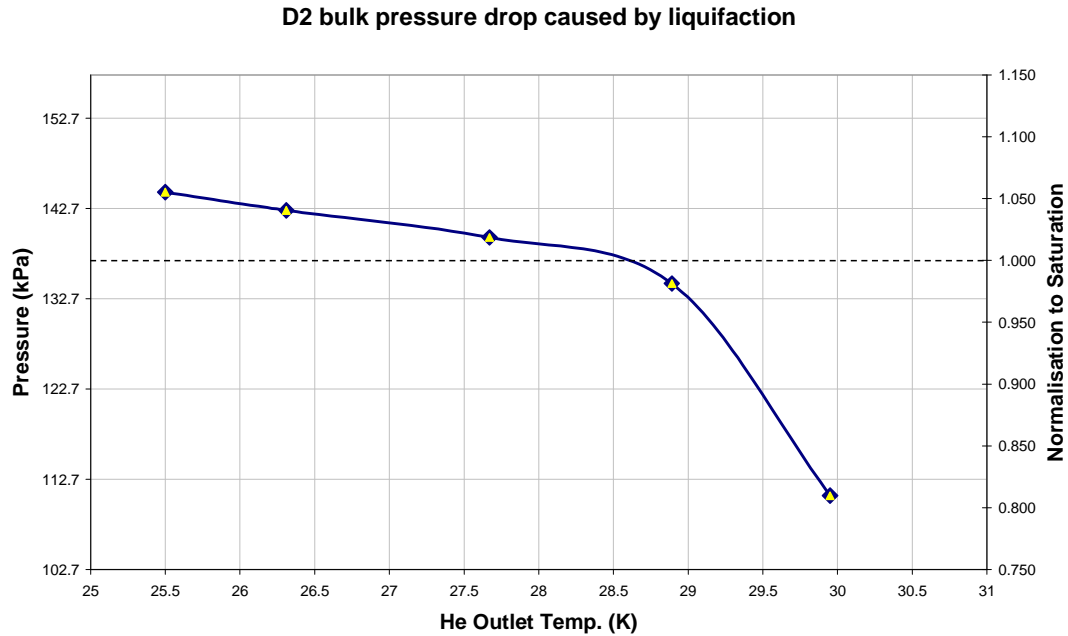
D2 bulk pressure drop caused by liquifaction

Figure 5 Reduction in deuterium pressure caused by deuterium liquefaction showing threshold behaviour above ~ 28.5 K. As in Figure 4, all the points are normalised to the value at the mid-point between the 3rd and 4th point, i.e. the chosen saturation point, and shown on the secondary y-axis.

4 Conclusion

Heat load measurements on the OPAL CNS demonstrate that all thermohydraulic design specifications have been adequately met. The measurements have been performed by steady state thermal balance in the helium coolant as functions of reactor power and CNS temperature. The measurements have been able to resolve individual components such as nuclear heat in liquid deuterium, nuclear heat in structural materials and non-nuclear heat. Threshold behaviour has been observed in liquid deuterium heat load and mass with increasing temperature, proving that at normal operating temperatures liquid deuterium remains in single phase in the In-Pile thermosiphon, well below saturation.

5 References

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