Modification of the CNS Helium Injection Logic

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Abstract.

The Cold Neutron Source (CNS) located at ANSTO's OPAL Reactor, Australia, utilises a helium cryogenic refrigeration loop to keep deuterium in liquid state for the production of cold neutrons. There exists two types of damage to the CNS in-pile structure which may potentially occur: (1) hot damage, where the CNS in-pile thimble overheats due to decay heat from the reactor core warming the in-pile with no available heat sink, and (2) cold damage, where great thermal stresses are induced on the in-pile assembly due to the large temperature difference of the room-temperature injected helium gas and the cryogenic temperature in-pile. The original protection logic supplied from the reactors' designer primarily focused on prevention of hot damage. However, a once-off undesired injection of helium into the vacuum containment brought potential cold damage into focus. Although this event did not appear to cause damage to the CNS in-pile structure, an administrative control was put in place to prevent reoccurrence. Upon further analysis, we modified the injection logic and developed an engineering solution, removing the need for an administrative control.

1. Introduction

OPAL's Cold Neutron Source (CNS) exists to provide 8 neutron scattering instruments at the neighboring Australian Centre for Neutron Scattering (ACNS) with cold neutrons [1]. The CNS in-pile is comprised of various individual process circuits: (1) helium refrigeration system (RCS) circuit, which removes heat from the in-pile liquefying the deuterium; (2) moderator system (deuterium) circuit, which moderates the neutrons from the reactor core to cold neutrons in the moderation chamber; and (3) heavy water circuit, which reflects neutrons back toward the moderator system increasing the neutron flux density in the deuterium. The CNS in-pile is housed within the vacuum containment vessel which has two primary functions: provide a vacuum environment to aid in thermal insulation of the CNS in-pile, and to prevent damage to the surrounding reactor sub-systems in the event of an hypothetical explosion or over-pressurisation event.

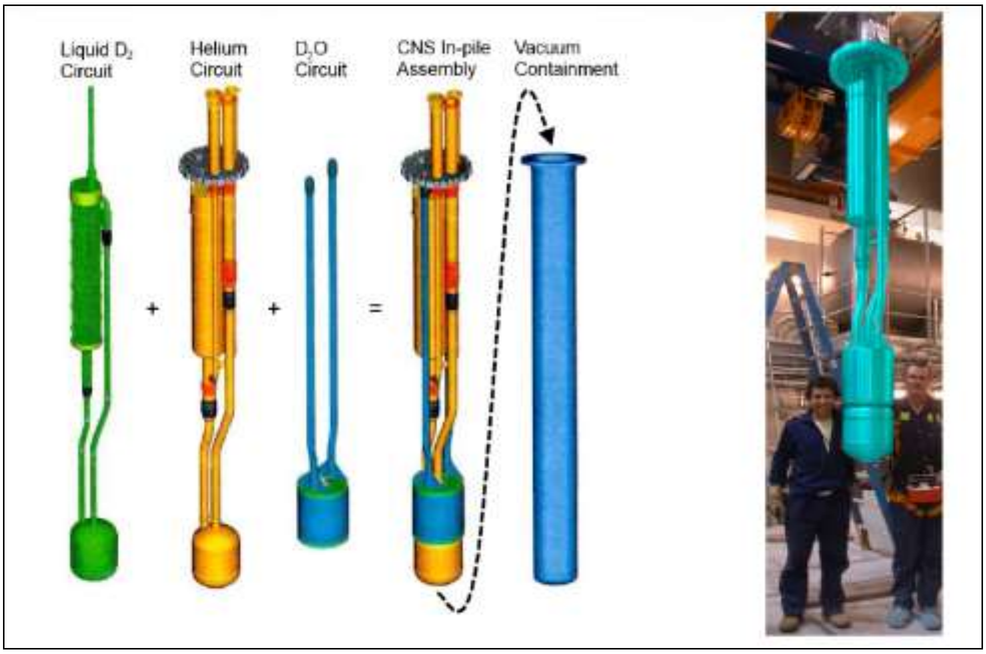


FIG. 1. Representation of the CNS In-Pile, showing the individual process circuits

The CNS operates in two modes, “STANDBY MODE” where the refrigerant helium flow by-passes the turbine and runs warm, and “NORMAL MODE” where refrigerant helium flow is cooled through the turbine and liquefies the deuterium, producing cold neutrons. When the CNS is not operational it is considered in “HALT” mode and there is no refrigerant helium flow. The refrigerant helium flow is a paramount process parameter to monitor because it provides a method of heat removal from the in-pile in both STANDBY and NORMAL modes.

If for some reason the refrigerant helium flow ceases, e.g. loss of site power (black-out) not only does the CNS enter HALT mode, but **the reactor will also trip**. The reactor power-state condition is interlocked to the CNS refrigerant helium flow. The reactor cannot restart until refrigerant helium flow is restored. It is this interlock in particular which highlights the importance of a fully functioning and reliable CNS to OPAL. Since OPAL is a multi-purpose reactor, other critical services are not able to be performed without an operational CNS including isotope production, silicon irridation, thermal neutron research and neutron activation.

Despite the reactor trip interlock being in-place, there is unavoidably a small amount of decay heat imparted on the CNS in-pile after a reactor trip without an efficient heat sink if deuterium is in gas phase, potentially enough to overheat and damage the in-pile. Therefore, to prevent hot damage, helium would be injected into the vacuum containment to provide a means of heat transfer to the heat sink (i.e. the reactor heavy water in the reflector vessel). Note that the helium used for injection comes from the gas blanketing system and is separate to the refrigeration helium, which forms a closed loop.

Conversely, if helium was to be injected with the CNS in-pile at cryogenic temperatures then there would exist the possibility of irreversible damage to the in-pile structure. The large temperature difference between the injected helium and the cryogenic structure would cause considerable stress and strain, leading to a possible in-pile failure event.

An additional consequence of helium injection when cryogenic which is not immediately obvious is the potential to cause heavy ice to form in the heavy water gap between the vacuum containment and beam tubes. It is unknown whether the vacuum tube or beam line can be structurally affected by the expanding ice as it solidifies in the narrow gap and the possibility of forming ice should be prevented.

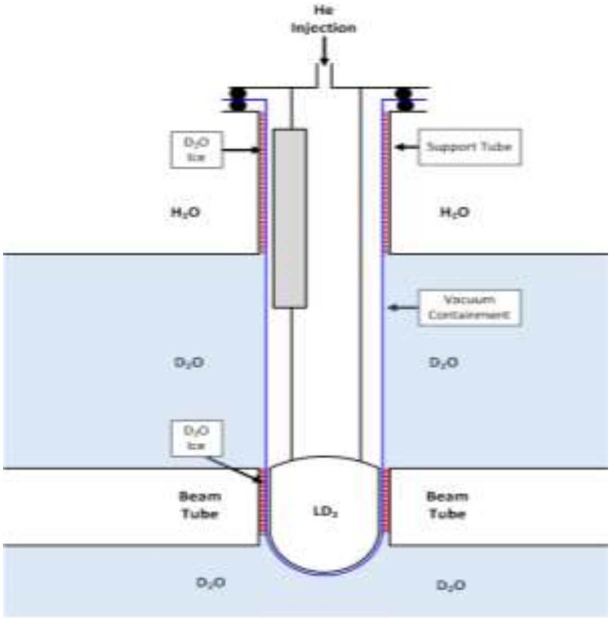
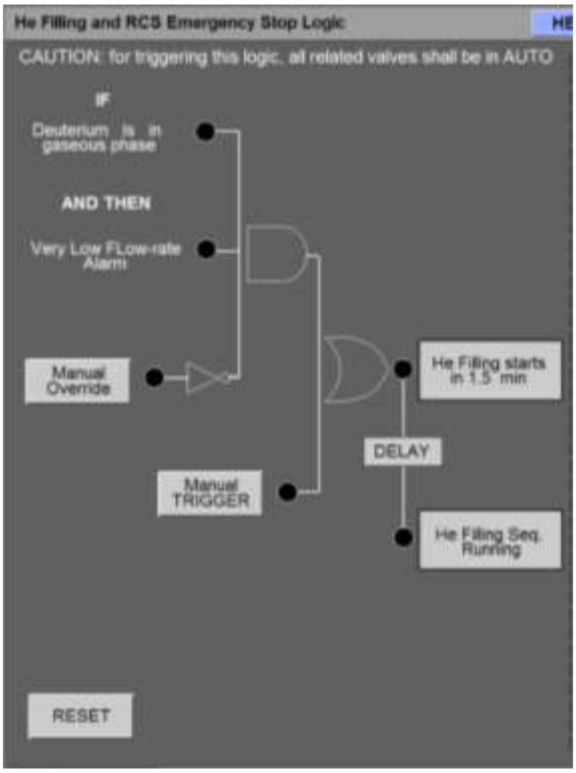


FIG. 2. Potential locations of heavy water ice formation.

To prevent the possibility of ice forming on the outside of the vacuum containment tube, the in-pile needs to be greater than 0 °C (273 K) at the time of helium injection.

2. CNS Helium Injection in the Spotlight

A renewed focus was shone upon the CNS when an undesired helium injection event occurred, causing room temperature helium to be injected into the vacuum containment with the in-pile at cryogenic temperature. The original logic allowed automatic helium injection if the following conditions were true: deuterium is vapor and then the refrigerant helium flow ceases (in that order). An internal bit in the logic stores to register the order has taken place.



CAUTION: for triggering this logic, all related valves shall be in AUTO

FIG. 3. Screenshot of Original Helium Injection Logic.

However, when the logic was reset after a reactor shutdown the following had occurred: refrigerant helium flow had ceased first, followed by natural evaporation of the deuterium after the CNS was left in HALT over an extended period of time. The internal bit was not held in place to prevent the helium injection, which proceeded after the regular 90 second countdown.

Although no damage to the CNS in-pile was observed after the once-off event, an administrative control was put in place to prevent this reoccurrence. The MANUAL OVERRIDE button was activated and kept on indefinitely during CNS operation, preventing ALL instances of helium injection (helium was manually injected when the Operator was sure the in-pile was at room temperature). This provided an "administrative" solution but ultimately does not engineer-out the problem.

What remained unknown to us at this point was how long the in-pile was able to absorb decay heat adiabatically (no helium injection and no refrigerant helium flow) before hot damage would occur. Furthermore, we were also unclear about how long after the trip we would have to wait until the in-pile naturally warmed to a safe temperature for helium injection. No previous investigative work or modelling had been previously performed which would provide a definitive answer.

3. Investigation and Modelling

We modelled the temperature rise and distribution in the event of a helium refrigeration flow trip and helium injection at cryogenic temperatures using computational fluid dynamic modelling.

To determine in-pile temperature rise in the event of a refrigeration flow trip (hot damage) modelling of the CNS in-pile was performed in five stages, shown by the different coloured lines in the graph below:

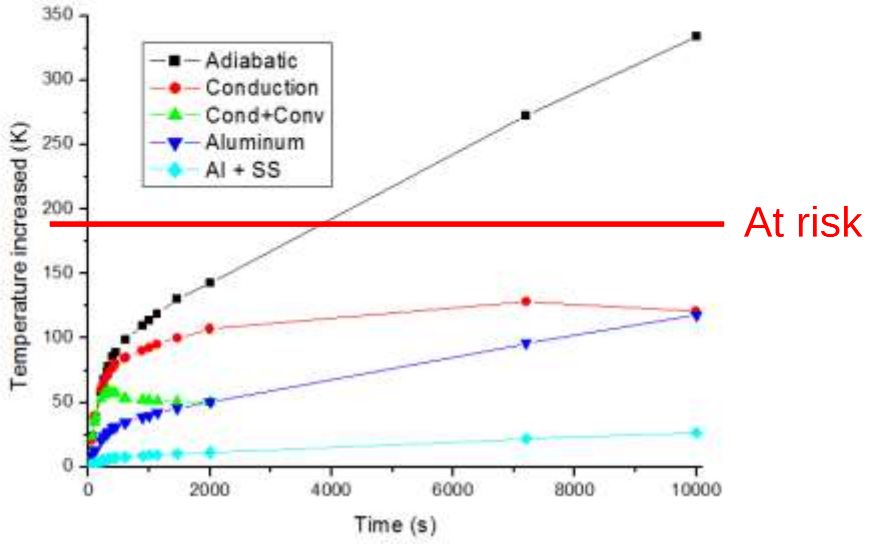


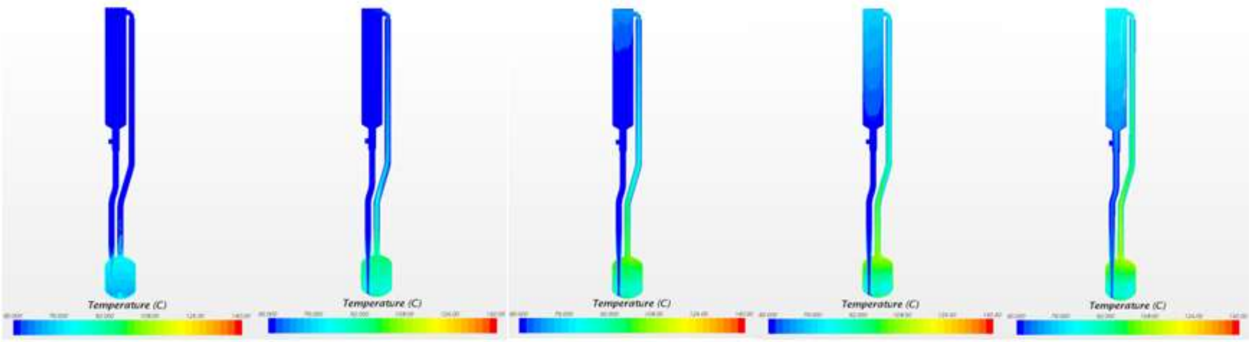
FIG. 4. Temperature increase of liquid deuterium in the Moderator Chamber in the event of a Reactor Trip 1

Adiabatic (black) line indicates the temperature evolution of the moderator chamber if the imparted decay heat was deposited so quick that the convection processes had not yet been able to draw the heat away. The mass of the moderator chamber is relatively small and the temperature reaches the “at risk” value after just over an hour.

The aluminium line (dark blue) indicates the temperature evolution of the moderator chamber and connecting aluminium pipework if the imparted decay heat was imparted adiabatically. Due to the increased connecting mass to absorb heat, the temperature evolution is not as sharp.

The Al + SS line (light blue) indicates the temperature evolution of the moderator chamber and connecting aluminium and stainless steel pipework if the imparted decay heat was imparted adiabatically. Due to the increased connecting mass to absorb heat, the temperature evolution is very slow to a point where the increase can be considered negligible.

The conduction line (red) indicates the temperature evolution of the moderator chamber with the absorption of heat into the deuterium. A natural thermosiphon loop forms within the deuterium, aiding heat removal away from the moderator chamber and distributing it within the whole in-pile structure itself.



(a) 1min (b) 2min (c) 3min (d) 4min (e) 5min

FIG. 5. Temperature evolution of the CNS in-pile in the event of a Refrig Helium Flow Trip - 5 min

The evolution of uniform heat distribution by the conduction in the deuterium thermosiphon can be further observed by running the simulation modelling to ten minutes.

FIG. 6. Temperature evolution of the CNS in-pile in the event of a Refrig Helium Flow Trip - 10 min

The red line reaches a maximum less than the “at risk” temperature difference of approx. 185 K at 330 seconds after a refrigerant helium flow trip, showing that the heat conduction effects of the deuterium alone is adequate to prevent hot damage.

Combining all the heat transfer effects together, the results of the modelling indicated the temperature rise (green line) is far from reaching the critical “at risk” temperature (shown as a red horizontal line). The mass of the in-pile and the conduction effects of the deuterium are great enough to prevent a large enough temperature rise to cause concern, proving hot damage is not a realistic scenario [2]. Hence, not only is helium injection unnecessary at any time after a helium refrigeration flow trip, but any action to prevent hot damage is also unnecessary.

We also performed an investigation into the stress effects on the injection of room temperature helium into the vacuum containment with a cold in-pile at 100 K (giving a temperature difference of 200 K). Results showed that even a 200 K temperature difference produced stresses on the moderator chamber of 460 MPa, above the allowable stress levels of

237 MPa [3]. In day-to-day regular NORMAL MODE operation the true temperature difference would be closer to 270 K. Hence the potential to cause cold damage is real.

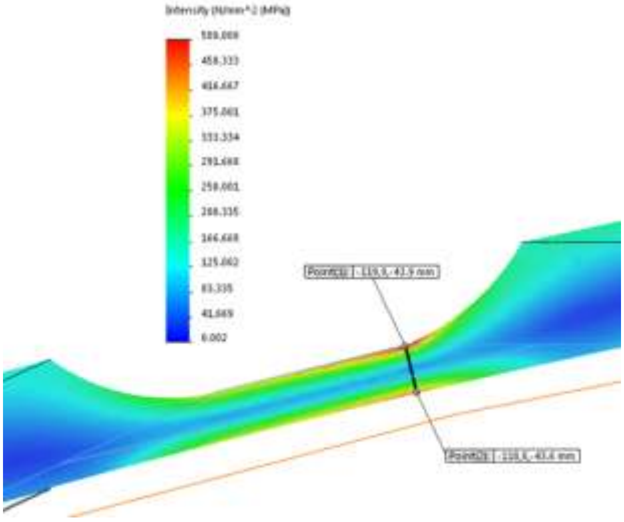


FIG. 7. Moderator Chamber - areas of localised stress greater than permissible levels during helium injection

With the computational fluid dynamics modelling demonstrating that hot damage was not a credible occurrence and cold damage was highly probable upon helium injection, we were now able to proceed to "relax" the logic to allow it to prevent cold damage.

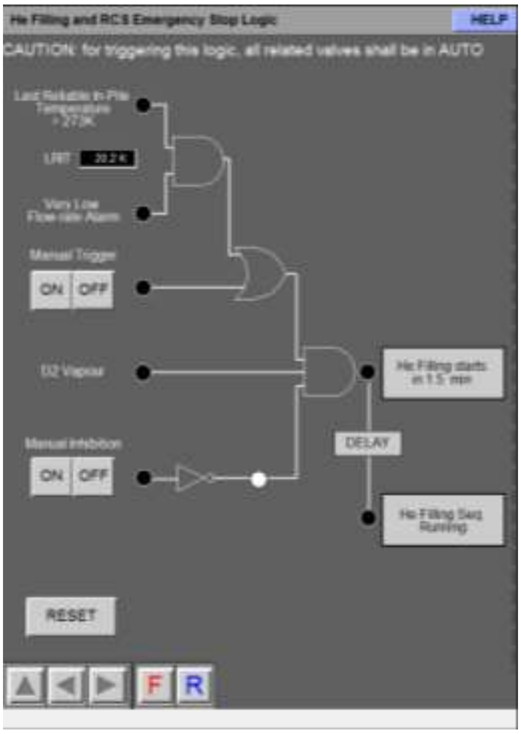
4. Development of the New Logic

In standard NO MODE operation the refrigeration helium enters the in-pile at a setpoint of 20.5 K, controlled by a heater through controller 6290-TI-710. Consequently, the temperature of the refrigeration helium when it leaves the in-pile is approximately 27.5 K (6290-TI-712), depending on the reactor power. Both these temperature sensors are located in the cold-box and not near the in-pile itself. Hence, there is no direct measurement of measuring the temperature of either the deuterium or refrigeration helium in the in-pile, but can only be estimated while there is refrigeration helium flow present.

The new logic requires the ability to "retain" what the refrigeration helium temperature was prior to a CNS trip. This lead to us creating a new variable called the "Last Reliable In-Pile Temperature", abbreviated as "LRIT", which would update while refrigeration helium was flowing, but retained its value when flow ceased. The LRIT takes its value from the inlet temperature of the refrigeration cryogenic helium.

Introducing the LIRT allows us to set a definite condition when the logic is able to automatically inject helium, as described below:
If the LRIT is greater than 273 K at the time refrigeration helium ceased then helium injection would proceed (adequately warm to prevent in-pile cold damage and icing).
If the LRIT is less than 273 K at the time refrigeration helium ceased then helium injection would not proceed (uncertain if the in-pile is adequately warm to prevent in-pile cold damage and icing).

The LRIT is a significant breakthrough in the modification of the logic as it takes away the decision to inject from the Reactor Operator and will never automatically inject if too cold. The LRIT is coupled to an AND gate to the very low refrigeration helium flow alarm, so both would have to be true as part for injection to proceed (helium would not automatically inject if refrigerant helium flow to the in-pile was flowing).



He Filling and RCS Emergency Stop Logic

CAUTION: for triggering this logic, all related valves shall be in AUTO

FIG. 8. Screenshot of Modified Helium Injection Logic.

The ability to manually inject helium and inhibit injection is still retained for maintenance purposes, although not envisaged to be used in everyday routine operation. The modified logic is no longer marred by the use an internal bit to store that deuterium is vapor prior to the refrigerant helium flow ceasing.

5. Conclusion

The new logic was successfully commissioned and tested during the August 2017 OPAL shutdown, acting as desired in all scenarios. Significantly, the long-standing holding permit to implement the administrative helium injection override was removed and formally closed. Since the logic has been implemented no undesired helium injections have occurred. It is not envisaged that the logic will require further modification.

6. References

[1] Bonneton, M., Lovotti, O., Mityukhlyaev, V. and Thiering, R., “Installation and testing of the OPAL (ANSTO) Cold Neutron Source,” IGORR 10 Conference Proceedings, Gaithersburg, DC, USA, 2005.

[2] Park, H. (ANSTO), “Computational Fluid Dyamics Analysis if Cold Neutron Source In-Pile System Using the Code STAR-CCM+”, OPAL-6200-TRP-002, Sydney (2015).

[3] ANSTO, “Thermal Stress Analysis of CNS In-Pile Assembly During Helium Filling”, OPAL-6230-DCA-002, Sydney (2015)

7. Glossary

TABLE I: List of terms and abbreviations used

Term	**Meaning**
CNS	Cold Neutron Source
RCS	Refrigeration Cryogenic System (refrigeration loop)
Refrigerant helium	The helium which flows to the in-pile. When the CNS is in NORMAL Mode this helium also flows through the turbine where it cools and liquefies the deuterium.
In-Pile	The physical structure of the CNS near the reactor core
Vacuum Containment	Vessel which houses the in-pile, designed to contain a rupture of the in-pile structure
Helium Injection	Helium from the gas blanketing system is injected into the vacuum containment
Hot Damage	Damage caused to the in-pile due to reactor decay heat, with no method to remove the heat
Cold Damage	Damage caused to the in-pile due to large stresses when helium is injected and the in-pile is at cryogenic temperature
Normal Mode	The RCS is running cold, i.e. helium flow through turbine cools the deuterium in the in-pile
Standby Mode	The RCS is running warm, i.e. helium flow bypasses the turbine but still flows to the in-pile
Halt Mode	The RCS is shutdown, i.e. no helium flow to in-pile
Moderator System	The pipework and part of the CNS in-pile which contains deuterium and moderates the neutrons from the reactor core
Moderator Chamber	Chamber at the base of the in-pile structure filled with deuterium (helium jacket) designed to maximise neutron flux