# NRU Main Cooling Circuit Heat Exchangers – Life After 50 Years Of Operation

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## Abstract

Continued operation of the National Research Universal (NRU) reactor is recognized as essential for AECL and the wider research community to sustain existing programs of national research, isotope production, and fuel and materials testing. To support its continued operation beyond December 2005, AECL initiated a NRU Licensability Extension (LE) Program, of which the NRU LE Plant Life Management (PLiM) Project is one of the major components.

As part of the NRU LE PLiM Project, a life assessment of the NRU heavy water main cooling circuit heat exchangers was performed. These heat exchangers have been in operation for 50 years and have provided excellent operational service to date. Inspection results show that the heat exchangers are still in good condition and the outcome of a rigorous and systematic assessment is that they have a good prognosis to achieve a further 10 to 20 years of service life. While recommendations have been made to support their continued operation, no concerns were identified as life limiting.

This paper will provide an overview of the integrated assessment of the NRU heat exchangers and the strategies that were applied in support of a further 10 to 20 years of service life.

## 1. Introduction

Even allowing for significant aging effects in Systems, Structures, and Components (SSCs), it is quite feasible that many Nuclear Power Plants (NPPs) will be able to operate for periods of time in excess of their nominal design lives, provided appropriate and proven aging management measures are implemented in a timely manner. This aspect has been recognized internationally by operators and regulators alike [1]. In general, NPP owners would like to keep their NPPs in service as long as they can be operated safely and economically. Although NRU is quite different from an operating NPP in many respects, its long-term operation is a good example of the feasibility to keep a reactor going far beyond the end of its originally intended life.

The NRU reactor has been operating at AECL's Chalk River Laboratories since 1957. It produces a high percentage of the world's medical and industrial radioisotopes, is used for research into reactor fuels, materials and components, and is the center for neutron beam research in Canada.

Approximately 10 years ago, it was anticipated that operation of the NRU reactor would not continue beyond the end of its operating license, set to expire on December 31, 2005. As this date approached, it was realized that the continued operation of NRU well beyond 2005 was essential to AECL and the broader research community. To support its continued operation, in 2003, AECL initiated a NRU Licensability Extension (LE) Program, of which the NRU LE Plant Life Management (PLiM) Project is one of the major components.

As part of the NRU LE PLiM Project, a life assessment of the NRU main heavy water cooling circuit heat exchangers was undertaken, and supports their continued operation for another 10-20 years.

## 2. Background

### 2.1 Aging Assessment Methodology

The overall approach adopted by the NRU PLiM Project is based on a comprehensive, multifaceted and integrated approach to address the underlying issues related to plant aging, to understand the relevant degradation mechanisms, and to develop appropriate mitigation plans. The program recognizes approaches used internationally and is consistent with their intent [1], [2], [3].

Aging assessments are a key element of a PLiM program. Aging assessments provide for the systematic and rigorous assessment of SSCs, and generally entail a review of data in order to assess aging degradation, establish current condition, and provide a prognosis for continued operation with associated recommendations. They include [1]:

- **Condition assessment (CA)** - Typically applied to less critical systems, structures and components (or groups of components called commodities). The methodology entails a general review of plant data in order to establish current condition and to evaluate aging degradation at a component level. The CA report provides a prognosis for attainment of design life and/or long-term operation with associated recommendations. Recommendations provide the technical basis for ongoing aging management of the subject structure, component or commodity and may identify a need for further assessment.

- **Life assessment (LA)** – Typically applied to the most critical structures and components that are generally passive in nature and typically designed not to be replaced as part of normal maintenance program. The methodology entails a detailed review of plant data in order to establish current condition and to evaluate aging degradation at a sub-component level. Similar to a CA, the LA report provides a prognosis for attainment of design life and/or long-term operation with associated recommendations. Recommendations provide the technical basis for on-going aging management of the subject structure or component and may be used for economic planning.

Identification of which aging assessment methodology is appropriate was determined early in the program based on screening/prioritization of SSCs to understand their importance. This is a risk-based methodology designed to identify not only the SSCs critical to safety and plant life, but also to prioritize the important process and auxiliary systems and equipment that contribute to the safety and reliability of the reactor.

As part of the screening process, an assessment of each individual SSC was carried out using predetermined evaluation criteria, and a quantitative ranking for each SSC was assigned by totalling a numerical score for the following four areas:

- safety function or classification
- risk of failure to facility safety
- risk of failure to public/worker/environmental safety
- risk of failure to production/operation

The ultimate objective of the program is to provide a health prognosis for continued operation of important SSCs beyond December 2005, with associated recommendations for additional short-term (10 years) and long-term (20 years) service. Additionally, the aging assessment methodology, through an evaluation of the Maintenance, Surveillance and Inspection programs in place, forms the technical basis for enhancements to existing aging management practices.

### 2.2 The NRU Reactor & Main Cooling Circuit Heat Exchanger Design

The NRU reactor is a heavy water-moderated and cooled reactor. The reactor operates at a maximum power of 135 MW (thermal), and a pressure slightly above atmospheric. The maximum coolant temperature is approximately 55ºC, approximately 250 ºC lower than a typical large power reactor. The coolant flow velocity is typically less than 10 m/s and is all single-phase flow. The product inventory is very small, about 5% that of a large power reactor. The NRU reactor has a negative power coefficient because all of its void, fuel temperature, and moderator temperature coefficients are negative. These are very benign operating conditions and characteristics.

Eight primary cooling circuits transfer heat produced in the reactor from the heavy water to the secondary process water coolant. Each circuit consists of a shell and tube heat exchanger and pump in series. These eight circuits operate in parallel between the top of the reactor vessel and the bottom header.

The main cooling circuit heat exchangers are a single-pass, counter-current, straight tube, shell and tube design, as shown in Figure 1. Each is capable of removing up to 50 MW of heat from the heavy water. Heavy water flows downwards through the tube side of each heat exchanger and is cooled by process water flowing upwards through the shell.

Main design features:

- All stainless steel construction
- 2,869 3/8” Outer Diameter (OD) straight tubes
- 7/8” thick shell
- Double tubesheets with leak-off connections in between
- Vertically oriented
- Heat exchangers are free to move - thermal expansion (such as between the straight tubes and the shell) is accommodated by the heat exchanger expansion bellows, external support design, and expansion joints in the associated piping.

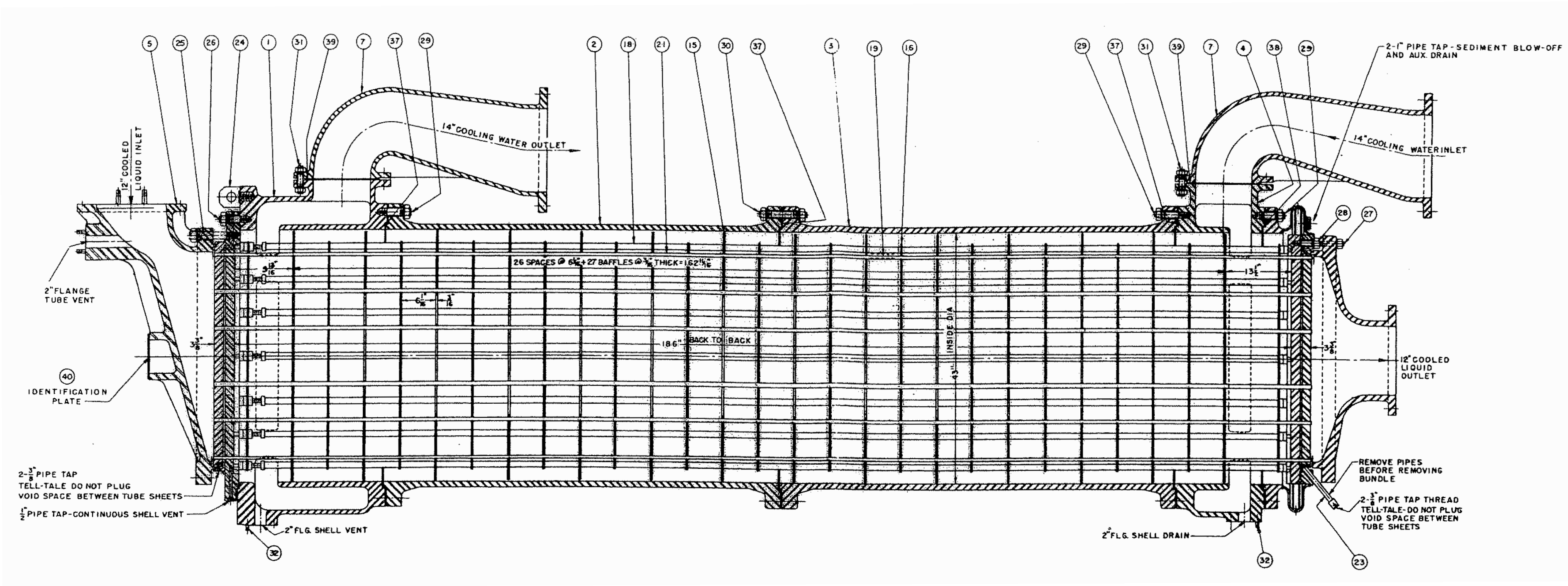


Figure 1: Heat Exchanger Schematic

The design and construction of the NRU reactor preceded the development of CSA Standards (CAN N285 Series) and Section III of the ASME Boiler and Pressure Vessel Code. Industrial standards and practice, which included large factors of safety, were used to design the reactor heavy water piping systems, vessels, and heat exchangers at the time.

During normal operations, the heavy water cooling circuit is a relatively low-temperature, low-pressure system as demonstrated by the following:

- On the heavy water side, $D_2O$ from the reactor enters the heat exchangers at 45-52ºC and exits at 33-37ºC after having been cooled by the process water
- On the process water side, water (direct from the Ottawa River) enters at a temperature of 1-20ºC depending on the season, and exits at 20-36ºC
- Heavy water flow through each heat exchanger is normally in the approximate range of 220-240 kg/s, and process water flow through the heat exchanger varies (114-199 kg/s) to meet the cooling demand
- Normal operating pressures are low, i.e. less than 25 psi on the tube side and less than 60 psi on the shell side

## 3. Heat Exchanger Life Assessment

Based on their significance to maintain cooling in the reactor (and a corresponding high screening score), a Life Assessment of the NRU heavy water main cooling circuit heat exchangers was performed.

The main steps in the process included:

- Definition of Scope – determination of physical and functional boundaries, interfaces, and design and performance expectations
- Screening – to establish which subcomponents should be assessed and to what extent (based on same methodology as used in SSC screening / prioritization described in Section 2.1)
- Review of Facility Data including:
    - Design, Manufacturing and Installation
    - Operating and Environmental Conditions
    - Chemistry
    - Transients
    - Event History
    - Maintenance, Surveillance and Inspection Activities
- Review of Industry Experience – covering potential degradation mechanisms and aging issues applicable to heat exchangers
- Personnel input from Interviews and Walkdowns
- Assessment of applicable aging degradation mechanisms for important subcomponents
- Conclusions, Health Prognosis and Recommendations

The systematic approach looks backwards at facility history in order to understand active aging degradation and the effectiveness of existing mitigation programs, as well as forward to identify potential aging degradation that hasn't necessarily been seen, but that should be considered, and ultimately to understand the prognosis for future operation. The resulting prognosis has associated with it conclusions and recommendations that are necessary for the prognosis to be valid.

## 3.1 Life Assessment Results

### 3.1.1 Looking Backwards

A review of industry operational experience with heat exchangers suggested a number of possible aging degradation mechanisms that should be considered. In the beginning, these could not be dispositioned with certainty for a number of reasons.

- Historical data available was limited. Over the many years of operation, no failures directly associated with the main heat exchangers had been reported. No tube, shell or tubesheet leaks have occurred in the past. This experience is good, although does not preclude the potential for failures in the future.
- A separate chemistry report indicated that the heavy water chemistry was well controlled with low anionic conductivity. The process water is injected with chlorine regularly but is not periodically analyzed. Traditionally, service water-cooled heat exchangers have been susceptible to degradation in a variety of industrial applications, especially on the secondary side/service water system.
- Records documenting NRU pre-start-up inaugural inspection results were not available and the heat exchangers were not included as part of a routine preventive maintenance program. Inspection and test results would normally provide a baseline for future inspections and also provide physical evidence as to heat exchanger condition.

With very little available data, rather than dismiss potential aging degradation a more conservative approach was taken and a need for more information was identified to help in dispositioning typical heat exchanger aging mechanisms.

### 3.1.2 Heat Exchanger Current Condition

To aid in establishing and documenting heat exchanger as-found condition, a heat exchanger inspection plan was developed and a number of activities were carried out in 2004/2005 in support of the LA.

One of the highlights of the inspections conducted is a video inspection of the secondary side internals of Heat Exchanger (HX) #7, conducted in November 2004. A video camera was inserted into the shell drain at the bottom of the heat exchanger and manoeuvred around the heat exchanger from the shell drain to the cooling water inlet (just above the bottom tubesheet). Inspection showed the secondary side of the heat exchanger to be quite clean. This is an exception to industry experience, which identifies fouling as the predominant aging mechanism (44.1%) causing heat exchanger failure/degradation [4]. In this case, the tubes, tie rods and baffles were practically free of deposits and appeared to be in very good shape. There was no evidence of any appreciable deposit build-up between tubes, nor at the tube-to-baffle joints, as shown in Figures 2 - 4. The internal surfaces of the shell, drain and cooling water inlet were clear, and had a rough appearance (which is expected due to the cast construction). The impingement plate (baffle in the vicinity of the cooling water inlet) was also intact and appeared not to have suffered any measurable amount of material loss, as can be seen in Figure 5.

Figure 2: Cleanliness of Secondary Side Internals

Figure 3: Tube Support Baffle, Tubing & Baffle Spacer

Figure 4: Tube-to-Support Connection

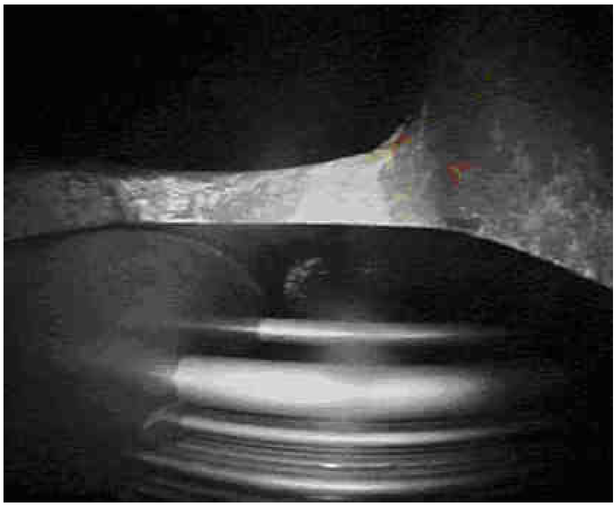

Figure 5: Process Water Impingement Plate

Pitting, crevice corrosion, and Microbially Influenced Corrosion (MIC) are all known to occur in CANDU systems, especially on open loop secondary side/service water systems. Experience with various heat exchanger failures in the earlier CANDU reactors have also shown that what was perceived to be good quality cooling water could, by concentration of impurities, turn out in practice, to be quite aggressive and has forced heat exchanger replacement [5], [6]. Failure was usually the consequence of through wall corrosion, which originated under a heavy layer of fouling on the shell side of the heat exchanger tube bundle that is cooled with lake water. For the NRU heat exchangers, the fact that the tube bundle is so clean is likely one contributor to the heat exchangers retaining their pristine condition.

A second video inspection of the primary side bottom tubesheet in HX #5 was also conducted in November 2004 wherein a video camera was inserted into the heavy water outlet through the elbow connection to the associated pump. Inspection showed the outer tubesheet to be in good condition as shown in Figure 6.

Figure 6: Bottom Inner Tubesheet

The tubesheets are constructed of Type 304L stainless steel, which, under the low operating temperature of NRU should be virtually immune to Stress Corrosion Cracking (SCC).

Other inspections were also conducted in support of the LA such as:

- Ultrasonic thickness measurements of the shell, head and expansion bellows
- Visual inspection of shell bolting
- Surface (dye penetrant) and visual inspection of the upper and lower heads
- Visual inspection of external supports

No significant degradation was observed. The results of these, combined with previous activities carried out by NRU (such as eddy current tubing inspection) formed the basis for establishing the current condition of the heat exchangers.

### 3.1.3 Looking Forward

As part of the LA methodology, a prognosis for continued operation is given (as poor, fair, good, or excellent) taking into consideration the following:

- The extent of aging degradation observed / current condition
- Potential aging degradation that hasn't necessarily been seen, but could occur
- Industry experience (as applicable)
- An evaluation of the existing maintenance, surveillance and inspection programs and their ability to detect, mitigate, and/or manage aging
- Potential failure consequences (safety and/or production)
- Whether a significant investment is required for continued operation

Overall it was established that the heat exchangers have a good prognosis to achieve a further 10 to 20 years of service life (based on limited similar experience to date elsewhere with long service heat exchangers with little evidence of aging-related degradation). Inherent to the prognosis is the assumption that operating conditions do not change and some recommendations were given in support of their continued operation. One such recommendation is to include the heat exchangers in a periodic preventive maintenance program, which includes thermal performance monitoring.

## 4. Conclusion

With a renaissance of the nuclear power industry, the focus is now on longer reactor design lives, and extending the operating life of existing NPPs. While NRU is quite different from power reactors in many respects, experience with the NRU heat exchangers is encouraging. The fact is that the NRU heat exchangers are in good condition after 50 years of operation. Their all stainless steel construction, relatively benign environment, and overall good operating practices likely contributed to their success thus far, and should continue to support a further 10-20 years of service.

## 5. Acronyms

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| AECL | Atomic Energy of Canada Limited |
| ASME | American Society of Mechanical Engineers |
| CA | Condition Assessment |
| CANDU | CANada Deuterium Uranium (registered trademark of AECL) |
| CSA | Canadian Standards Association |
| HX | Heat Exchanger |
| IAEA | International Atomic Energy Agency |
| LA | Life Assessment |
| LE ` | Licensability Extension |
| MIC | Microbially Influenced Corrosion |
| NPP | Nuclear Power Plant |
| NRU | National Research Universal |
| OD | Outer Diameter |
| PLiM | Plant Life Management |
| SCC | Stress Corrosion Cracking |
| SSC | Structures, Systems and Components |

## 6. References

[1] International Atomic Energy Agency (IAEA), "Nuclear Power Plant Life Management Processes: Guidelines and Practices for Heavy Water Reactors", IAEA TECDOC-1503, June 2006.

[2] International Atomic Energy Agency (IAEA), "Implementation and Review of Nuclear Power Plant Ageing Management Programme", Safety Report Series No. 15, Vienna, 1999.

[3] International Atomic Energy Agency (IAEA), "Methodology for the Management of Aging of Nuclear Power Plant Components Important to Safety", Technical Reports Series No. 338, Vienna, 1992.

[4] Booker S., Lehnert D., Daavettila N., and Palop E., "Aging Management Guideline For Commercial Nuclear Power Plants – Heat Exchangers", SAND93-7070, prepared by MDC-Ogden Environmental and Energy Services under contract to Sandia National Laboratories for the U.S. Department of Energy, Washington, D.C., 1994.

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[6] Brennenstuhl A.M., Doherty P.E., Bellamy G., King P.J., and Dunstall T.G., "The Corrosion of Freshwater Cooled Nuclear Heat Exchangers At Ontario Hydro", Conference Proceedings, Steam Generator And Heat Exchanger Conference, Toronto, 1990.