NIST REACTOR SOLVES OPERATIONAL NUISANCE PROBLEM USING NOVEL APPLICATION OF VACUUM TRANSFER TECHNOLOGY

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ABSTRACT

The 20 MWt test reactor operated by the National Institute of Standards and Technology (NIST) Center for Neutron Research provides neutron radiation for a wide variety of research programs. This reactor had been operating with an ever increasing number of tiny leaks in an auxiliary system that is designed to cool the reactor thermal shield. These leaks and their immediate consequences required constant attention, including regular applications of various leak stoppage products and aggressive operational management of the cooling lines as well as the containment of loose contaminated coolant. After establishing the engineering concept and proof of the theoretical principle through the development of various prototypes, NIST made the decision to permanently mitigate the issue by modifying the accessible part of the system to operate under vacuum rather than positive pressure. To this end NIST hired Merrick & Company (Merrick), an engineering and architecture firm with experience at Department of Energy (DOE) nuclear facilities, to design and implement the upgrade based on the various prototypical efforts. A successful effort would increase the reliability of the reactor, which has a favourable impact on the availability of the NCNR, which is operated as a user facility. With the work now complete and the facility having successfully operated through its first several post-upgrade cycles, the effort appears to have been successful, with potential lessons-learned for other reactors, as well as for many other applicable industries.

1 Introduction

The National Institute of Standards and Technology (NIST) operates a 20 MWt nuclear test reactor, known as the National Bureau of Standards Reactor (NBSR). The NBSR is part of the NIST Center for Neutron Research (NCNR) and serves as a steady state source of neutron radiation for the purpose of conducting scientific and engineering research.

Since the NBSR's first criticality in 1967 the NCNR's contribution to the scientific and engineering community has been considerable. Research at the facility has led to upwards of 6000 scientific and technical papers with many of them appearing in high impact journals. In addition, hundreds of students have earned their doctorate degrees based on research that was conducted at the facility. Work at the NCNR has been honoured with more than 30 national awards and prizes from a wide range of prominent scientific and engineering organizations.

The scientific work performed at the NCNR is diverse. For example, in one particular class of applications, directing neutrons at (and scattering from) solid state substances allows scientists to visualize the hydrogen atoms within them, providing valuable insights into material structure and its relationship to material performance that cannot be accomplished by any other means. Participants have made use of the NCNR's neutrons to further scientific understanding in hundreds of technical fields including super conductivity, fuel cells, motor oils, metallurgy, and magnetism (e.g. for digital storage media). The facility has even been used to study the pigments and techniques of Renaissance masters, and has allowed researchers to "see" a heretofore unknown self-portrait by the Flemish painter Anthony van Dyck hidden under one of his other masterpieces.

Open to industry, government and academic users, through a peer-reviewed application process, the NCNR receives some 2000 research requests for "beam time" each year. The NCNR is typically oversubscribed by a factor of 2 to 3, with its staff working towards making the facility available to as many worthwhile research projects as possible. Excluding planned reactor shutdowns, NCNR staff has operated the reactor with a near 100% efficiency record in scheduling and reliability. This is a remarkable result, particularly considering the fact that since shortly after its first criticality in late 1967 there has been a problem with an auxiliary cooling system that is designed to cool a shielding wall that is integral to the NBSR’s biological shield. The problem centred around the behaviour of 9.5 mm diameter copper pipes that guide coolant to this shielding wall. The pipes are thought to have developed low cycle thermal fatigue cracks, leading to leakage of high purity de-ionized cooling water, potentially leading to less effective cooling of the thermal shield in adjacent areas. This issue has never presented a reactor safety problem, but it has always been a serious operational one, in that if too many cooling pipes are unable to carry water due to their individual leak rate, the reactor could not run without the shielding wall locally overheating. For years NCNR staff had mitigated this issue by strategically applying various leak stoppage products, such as fibres, clays and resins, during scheduled shutdowns as well as monitoring each pipe during operation and selectively shutting off those pipes that through their observed pressure and flow behaviour indicated they might contain a leak. In addition, any water that escaped through the leaks had to be gathered and properly disposed of as low level radioactive waste. Finally, the level of the system water supply had to be continuously monitored in what was originally designed to be a closed loop system.

Over time these problems slowly worsened, requiring ever more time and effort to manage. The long term outlook was that this development would eventually jeopardize the scheduling reliability of the NCNR, which is considered to be the key to its continued utility to the scientific and engineering community.

Therefore in 2006, the NCNR started a research project with the aim to identify a method to maintain coolant flow in the thermal shield cooling system such that there would no longer be a need for any maintenance of the interior of the cooling pipes. Several approaches were proposed and studied. For various reasons, one of these quickly showed itself to have an unusually high potential to address the thermal shield problem once and for all: moving the coolant by means of a vacuum transfer technique.

2 The NCNR reactor

In order to understand the solution that was developed by NIST and eventually implemented through a team of contractors led by Merrick, one needs to get a better idea of the design of the NBSR and its thermal shield cooling system, since every reactor (and the NBSR in particular) tends to be "one of a kind".

The NBSR is a 20 MWt heavy water moderated and cooled reactor, featuring a core box consisting of 30 fuel elements built from aluminium clad fuel plates. The core box is located in a reactor vessel (diameter approximately 1.4 m) that is filled with moderator. Surrounding the outside of the reactor vessel is an approximately 1.5 m thick monolithic concrete annulus that acts as a biological shield protecting the outside world from reactor generated gamma radiation. In-between the reactor vessel and the biological shield is the tubular thermal shield consisting of an approximately 1.5 m diameter steel tube of 100 mm wall thickness, clad with 50 mm of lead on the inside. The exact dimensions are not important for the purpose of this paper. What is relevant, however, is that there is a 25 mm radial gap between the lead cladding and the reactor vessel. This gap is continuously purged with carbon dioxide (CO_2) gas in order to displace the ambient air. This is done because naturally-occurring argon in air (approximately 1%) forms a radioactive isotope when exposed to neutron radiation emanating from the reactor. As this would create an unacceptable effluent disposal burden for the NBSR, the air is substituted by CO_2, which contrary to air does not contain any constituents that can be activated.

The function of the lead and steel in the thermal shield is to protect the concrete of the biological shield by significantly reducing the gamma dose rate reaching it. This process deposits heat into the thermal shield, which must be removed to maintain temperatures in an acceptable range. By design, the necessary cooling is achieved through an array of 188 parallel 9.5 mm ID copper pipes soldered onto the inside of the steel tube and otherwise completely surrounded by the lead cladding. Neighbouring pipes have opposing (up and down) flow directions. Each pipe is run from the supply header to the return header and passes through the lead only once. The original design called for high purity de-ionized water as the coolant, which was originally pumped in at a flow of 4 L/min per pipe. The thermal shield is capped with steel at its bottom. This cap is also clad with lead into which an additional 32 copper pipes are embedded.

It is mainly within the array of vertical cooling pipes that the leaks formed. It is hypothesized that the differing heat expansion characteristics of the copper lines and the materials in which they are encased, as well as the thermal cycling provided by the reactor on/off cycle, provided the conditions for a low cycle fatigue mechanism to establish itself, thereby causing an on-going trend of small crack formation.

Since there is no way to examine the pipes, it is not possible to determine where the holes are, nor where any water found in the basement might actually be originating, but the individually impacted pipes can be identified by reading the pressure gauge that is installed on each pipe, while operating the isolation valves belonging to that pipe. Once every reactor operations shift all individual pipes were isolated from the headers one by one. If their internal pressure did not increase, it is assumed the pipe was leaking (i.e. the contents of the pipe bleeds off into the biological shield). If the pressure in the pipe increases (presumably due to the heat deposited into it by the reactor) it is assumed to be functional. Leaking pipes identified in this way during reactor operation would be shut off for the remainder of that cycle, while maintaining a balance between the need for cooling the thermal shield and the desire to minimize the quantity of nuisance water leaking from the system into the building basement. This means that if too many leakers were identified in a particular sector, one or several would be allowed to continue leaking. Then, every 38 days, during the regular shut-down for refuelling, operations crews would perform the labour-intensive process of applying leak stoppage products to each impacted pipe, attempting to plug up the holes from within. Unfortunately, the same expanding/contracting mechanism that caused low cycle fatigue cracks in the pipes to begin with, also tended to work loose these plugs, often as soon as the next operating cycle.

As noted, the need for these mitigation procedures was slowly increasing as more pipes developed leaks and repairs were required more frequently, creating a risk to the operational record of the NBSR, which would have the potential to harm the scientific programs of the NCNR.

As part of the research project that aimed to establish a permanent “fix” for the thermal shield problem, interviews with operations staff were conducted. These interviews yielded an important clue in that it was reported that if the flow rate (and thereby the average pressure) in the existing thermal shield was lowered, it was found that parts of the plumbing system would find themselves under a vacuum due to a siphoning effect. The result of this condition is that gasses from the surroundings were admitted into the cooling water.

It was conjectured that if the system were to run below atmospheric in its entirety, such that even the lowest point of a cooling loop would be below atmospheric pressure, any and all exposed leaks would admit gasses into the coolant rather than allow water to leak into the environment. This mode of operation would be akin to the operation of a perforated soda straw.

Upon further research, some information was found about a 10MWt reactor, the High Flux Australian Reactor (HIFAR) near Sydney, Australia, that had successfully converted their thermal shield cooling system from positive pressure to vacuum operation to mitigate problems with their thermal shield.

Despite the encouragement provided by the Australian finding, there were a number of important differences between the NBSR and HIFAR. For one, the flow requirements of the NBSR thermal shield were about five times that of the HIFAR thermal shield, necessitating a far larger system and a greater pumping capacity. In addition, with its "188 + 32 pipe" set up, the NBSR system would require the addition of a lot of wear-prone and friction-creating mechanical devices (flapper pumps) if directly following the Australian solution model. As NIST engineers analysed this problem, they hit on the possibility of generating a vacuum using an eductor driven by the coolant medium itself. An eductor has no moving parts and can be scaled up to almost any size making it an ideal candidate for testing in a series of prototypes of incrementally increasing size and reach without adding conceptual complexity.

Besides size differences, an even more problematic difference with HIFAR was the fact that, when under vacuum, the pipes with the cracks, while no longer "pushing out" water, would be "sucking in" the gases around them. For the NBSR, unlike at HIFAR this meant not ordinary air, but CO_2 purge gas would be admitted into the water. This generates carbonic acid, potentially causing it to corrode the inside of the copper piping.

Fortunately a perfect solution was found by NIST engineers. Calculations suggested that saturating the coolant with magnesium carbonate, thus turning the CO_2 laden coolant into a bi-carbonate buffer, would, bring the pH of the coolant back to a neutral pH=7. In comparison, for example, they found that calcium carbonate, a chemical with similar properties as magnesium carbonate, would only bring the water to a still-too-acidic pH=6. Furthermore, magnesium happens to be an element that displays minimal effects of neutron activation, and to the extent that it does activate, the dose rate is very limited. Lastly, most metals of which traces would dissolve in the cooling water (and which would cause activation problems) have insoluble carbonates. The abundance of magnesium carbonate forces these metals to be precipitated as solid carbonates, which can be separated from the coolant by filtration. It should be pointed out that due to the presence of an abundance of magnesium carbonate, the ion exchange system that was responsible for keeping the water clean prior to the change to vacuum operation could no longer be used, since it would indiscriminately extract the magnesium carbonate, which would quickly overwhelm the ion exchanger.

The concepts laid out to this point 1) moving water while an entire plumbing system is below atmospheric; 2) using a coolant driven eductor as the vacuum pump and 3) using magnesium carbonate to create a bi-carbonate buffer out of a CO_2 solution, 4) the presumed benign behaviour of magnesium in a neutron activation environment and 5) magnesium carbonate as a precipitation agent for metallic trace elements that are prone to activate, were tried out in a succession of prototypes. The prototype development process was started by designing and building a one line test stand that was designed to act upon a real reactor tube followed by a six line visually transparent (PVC) system that operated outside of the reactor environment. Eventually in 2008 NIST contracted with Merrick to review and critique the prototypical efforts and scale up into a full up design that can be implemented.

3 Proving out the concept at full scale

While all of the concepts looked good on paper and in limited scale (one and six line) testing, in an effort to mitigate risk NIST directed Merrick to prove them offsite at full scale. To this end NIST specified a Factory Acceptance Test (FAT) and Merrick proceeded to design and build the full scale model of the system at a Colorado fabrication facility owned by one of its sub-contractors.

Merrick built an array of 188 five meter tall plastic tubes to simulate the "hidden" copper tubes encased in the thermal shield. Since they could not know the actual number, size or location of the holes that would be existing in the real pipes, a large contingency was added by punching an abundance of holes in various tubes to create a scenario far more challenging than reality, and testing that the suction was maintained and that water did not emerge from the tubes under vacuum. Through empirical testing and retesting, a complete system was created that, all were confident, would work exactly as envisioned at the NCNR facility.

Meanwhile, Merrick deployed teams of electrical and mechanical subcontractors to carefully examine and measure mechanical, electrical and other conditions at the NCNR facility. Concurrent with this effort, Merrick hired another subcontractor that developed the control software that would be necessary to keep pressures, temperatures, flow rates and other variables at the required values.

Subjected to the elaborate FAT, it was established that the system met or exceeded all of its functional requirements. The system was disassembled, crated and shipped across the country, meanwhile organizing it in such a way that the subcontractor teams could readily put it back together and install it at the NCNR. A number of back and forth visits were required, and a intricately conceived construction plan was developed, which involved careful labelling of hundreds of parts and subassemblies along with a customized manual of engineering instructions.

4 Meeting onsite challenges

As the new system was in transit, the various teams began removing the components of the old system in accordance with the plan. Effectively, the system needed to be "plugged in" to an extremely limited and congested existing area, with high precision. Interfaces where old piping, components or equipment were to be removed and new ones were to be joined had to be cut or prepared to relatively tight tolerances. Piping and other aspects of the new system needed to account for experimental equipment and other existing components that would remain in the area, and needed to be built around them.

In addition, the plan called for reusing several pre-existing components of the old system, including a heat exchanger, a filtering system, and, especially, a large copper water tank which was deemed too heavy to move and too expensive to dispose of. Ironically, it was a fairly non-technical aspect of the project that ended up being one of the most problematic, as the team found it challenging to weld the thick copper.

Also challenging was the fact that, in this project, as is the case in most commercial nuclear facilities, there is a very limited ability to get close to the reactor area. Part of the elegance of the solution is that it allowed the design to successfully "click in" to an existing outside infrastructure, with major parts of the existing system—indeed, the pipes themselves—wholly unseen and unaltered.

But perhaps the biggest challenge was installing the system within the confines of an 11 month long planned reactor shutdown schedule, where dozens of other upgrades and activities, including the installation of new experimental beam lines, were also underway. Significant coordination was needed in order for all teams to maintain their commitments and stay out of each other’s way.

5 Hard work—and teamwork—leads to success

The project was completed on schedule, with Merrick training of NCNR personnel, as well as implementing a full commissioning process, before turning over the keys. But Merrick was not out of the picture: as part of the contract, NIST had asked for and Merrick had agreed to a one year warranty, fairly unusual in the industry. After the extensive testing and success of the full up system, during the FAT and the site acceptance test at the NCNR, Merrick, who had handled every aspect of the project from design to commissioning, was confident in the quality of the work performed and the ability of the system to perform as intended.

As this paper is being written, the new cooling system has completed several reactor operating cycles. For the first time in decades, it was able to work with all pipes open, thereby providing what is believed to be the most effective and complete cooling to the thermal shield that the facility had experienced since the late 1960s. Further, no or little leaked water has been detected. As a result, the recurring maintenance on the individual lines appears to no longer be necessary, allowing the facility to reclaim significant operations labour time that can now be used for other purposes.