Improvements Made to the Bruce A Upgraders and Heavy Water Cleanup System as Part of the Bruce A Units 1 and 2 Restart Project and Commissioning Results

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Abstract

As part of the Bruce A Units 1 and 2 Restart Project, major modifications and maintenance were completed on the heat transport and moderator upgraders and the heavy water cleanup system. This represents the first time that major rehabilitation has been done to such systems in a CANDU nuclear station for the purpose of life extension. Prior to shutdown in 1997, the upgraders and cleanup system significantly underperformed against the stated design. The rehabilitation, which included major design changes and implementation of new systems, resulted in the upgraders exceeding design throughput and making product with quality much better than specified. This paper describes the work done, results from inspections and follow-up, and performance data from commissioning.

1. Introduction

In May of 2001 Bruce Power became the licensed operator of the Bruce A and Bruce B Nuclear Generating Stations located in south western Ontario on Lake Huron. There are eight CANDU nuclear reactors on site. At the Bruce A plant, Units 3 and 4 were restarted in late 2003/early 2004 after a lay-up period of approximately 5 years. Units 1 and 2 have recently undergone rehabilitation and were restarted in 2012. The Bruce B plant (Units 5 to 8) has been in continuous operation since the mid-1980s.

Each plant has a dedicated heat transport (HT) and moderator upgrader to upgrade downgraded heavy water to useable, high purity (i.e. high isotopic) heavy water. During the time that Units 3 and 4 were in operation, the Bruce B upgraders were providing high isotopic heavy water to both Bruce A and Bruce B. However, the restart of Units 1 and 2 requires the operation of the HT and moderator upgraders at Bruce A in order to provide makeup heavy water to all 4 Bruce A operating units.

Prior to shutdown in 1997, the Bruce A HT upgrader could not achieve a feed rate greater than 80 kg/hr with 70 wt% isotopic feed and could not produce bottom product having the minimum required isotopic of 99.2 wt%. When it operated at the design feed flow rate of 120 kg/hr, the bottom product had an unacceptable isotopic of 97 wt% [1]. As holes plugged in the distributors that are located above each packed section, operators would reduce the feed flow rate to maintain the required bottom product purity. When flow reduced below 50 kg/hr, the HT upgrader was shutdown, and the distributors were cleaned. This took place every 12 – 14 months. At the time of shutdown, it was believed that the main cause of low feed flow rate was deterioration of the structured packing and frequent plugging of distributors.

The moderator upgrader did not experience distributor plugging. It was able to produce high isotopic water (greater than 99.92 wt% isotopic) at the design feed flow rate of 220 kg/hr when upgrading moderator water from the operating units, and at the design feed flow rate of 25 kg/hr when upgrading downgraded moderator water having 35 wt% isotopic [2].

The return to service of the Bruce A upgraders was part of the Bruce A Units 1 and 2 Restart Project. It consisted of 4 major projects:

1. Modifications and maintenance to the HT upgrader

2. Modifications and maintenance to the moderator upgrader

3. Replacement of the control system and control valves, maintenance of field instruments

4. Installation of ultraviolet (UV) – peroxide based heavy water (D_2O) cleanup system

Engineering, maintenance and installation were performed by SLN AECON, a joint venture between SNC Lavalin-Nuclear Inc., and Aecon Group Inc. Commissioning was performed jointly by an integrated team consisting of Bruce Power and SLN AECON personnel. Engineering work started in late 2006. Engineering packages were released to the field beginning in 2007. Commissioning of the various systems, beginning with the HT upgrader started mid-2009. The HT upgrader was placed in-service in late 2010, followed by the moderator upgrader in mid-2011. The UV oxidation system was placed in-service in late 2011.

This paper describes the work done to return to service the Bruce A upgraders and the implementation of the new UV oxidation equipment to the cleanup system to reduce plugging of the HT upgrader distributors.

2. Heat Transport (HT) Upgrader

2.1 Background

Figure 1 shows an overview of the HT upgrader. The HT upgrader consists of two Sulzer packed vacuum distillation towers connected in series, a falling film reboiler, head condenser, feed system, bottom product takeoff system, head product takeoff system, three main auxiliary systems (vacuum system, sample system, collection system), interface systems (common service water, chilled water, steam/condensate, instrument air, electrical systems) and a control system. All the upgrader equipment is located in the Ancillary Services Building (ASB) at Bruce A.

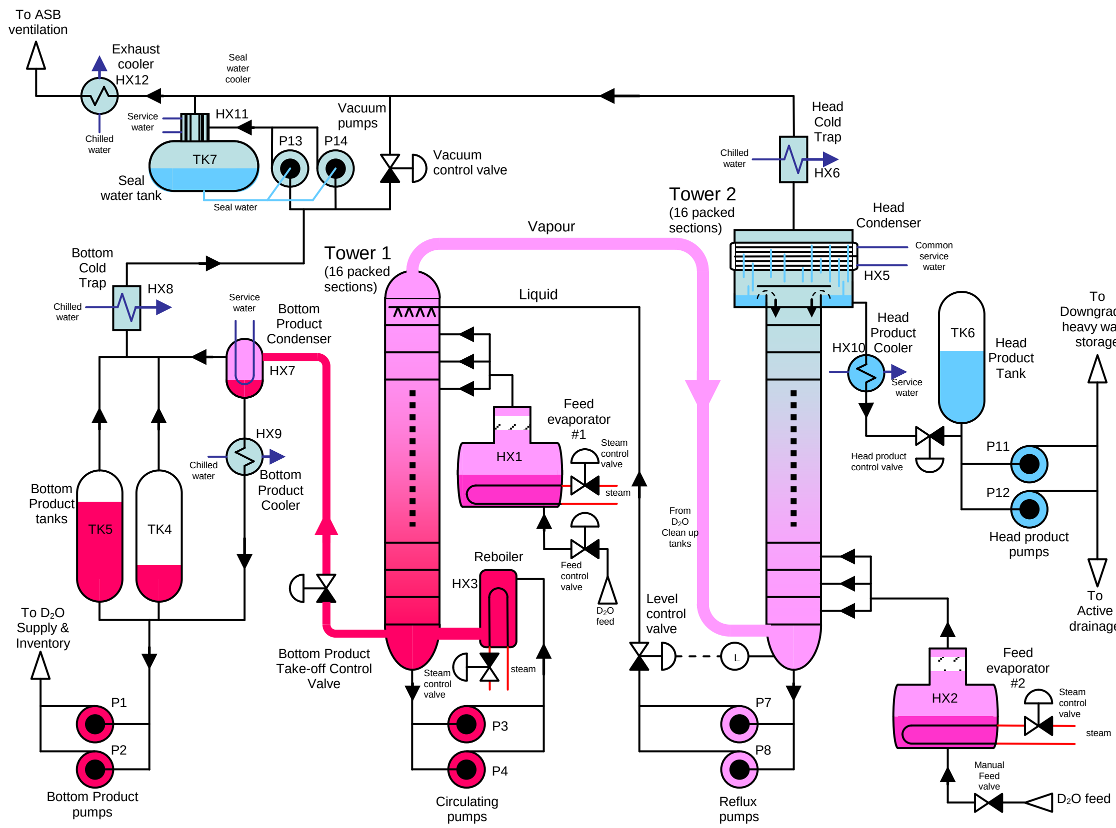


Figure 1 Schematic of Heat Transport Upgrader

2.2 Design and Implementation

The engineering activities targeted critical process equipment to improve overall system performance and control. Engineering work began in late 2006 and focused on the modernization of the control system as well as the replacement of pumps, control valves and transmitters, with special consideration given to capacity, sizing and integration to the modernized control system. The reviews and approvals of the engineering packages were completed in compliance with Bruce Power's Engineering Change Control (ECC). The modifications also addressed design aspects in additional areas of Reactor Safety, Human Factors, Fire Protection, Environmental Qualification (EQ), Operator Training etc. Further, maintenance requirements for the new equipment identified critical spare parts/inspections and were integrated with the Utility's maintenance program. Regulatory reviews of engineering packages were completed with the Canadian Nuclear Safety Commission (CNSC) and Technical Standards and Safety Authority (TSSA) prior to their release for field installation. The major engineering scope was as follows:

2.2.1 Replacement of mechanical sealed liquid pumps with canned motor pumps

The mechanical seal pumps were a major source of air ingress, which resulted in the inability to maintain vacuum in the towers at the desired set point. Furthermore, cavitation in the circulating and reflux pumps caused frequent shutdowns for pumps maintenance. Engineering consideration was given to mitigate potential for cavitation in the recirculating and reflux pumps without making major (and costly) changes to the legacy piping configuration. Pump sizing and section, together with an option to include an inducer to decrease the NPSH required addressed the issue and was validated during commissioning. In total 8 pumps were installed.

2.2.2 Replacement of vacuum pumps

Engineering consideration was given to vacuum pump capacity because of the critical operating requirement of maintaining upgrader tower pressure. Due to the efficiency of the new Burkhardt vacuum package and the tightness of system joints (reducing air ingress), the commissioning team was challenged to maintain sufficient load on the pumps and maintain the 14-17 kPa(a) set point. This issue was resolved by modifying the instrument air supply so that instrument air was supplied to the towers. The additional load allowed the vacuum pumps to maintain tower vacuum within the acceptable operating ranges. In total 2 pumps were installed.

2.2.3 Support services – replacement of refrigeration units (chillers)

The maintenance program initially specified only oil replacement for the chillers. The units failed pressure testing three times and required engineering selection of new units for installation. As this modification was a late addition to the project schedule, one chiller unit was refurbished using parts from the other chiller until the new replacement units were installed.

2.2.4 Support services - replacement of condensate pumps

The replacement of the two condensate pumps was critical as the condensate system was a shared system service between both the HT & moderator upgraders. The pumps transferred collected hot condensate from a common tank. The condensate pumps were integrated with the Distributed Control System (DCS) to allow operators to control the pumps from the control system. One of the main challenges was the lead-lag pump logic to alternate pump duty cycle. Based on the control logic initiated from tank level, the 1st pump would initiate pump down. However if level continued to rise, the stand-by pump would start up. The next time the condensate tank was pumped down, the pumps would alternate being the lag and lead pumps. In this way, the pump motors would share duty. Despite ongoing trouble-shooting, the instrumentation remains an outstanding item. It was believed that excessive turbulence of condensate in the tank caused erratic tank level readings and rendered the control for lead-lag functionality erratic.

2.2.5 Maintenance

The maintenance activities were defined by Bruce Power's work management system and included pre-shutdown identified deficiencies and outstanding periodic maintenance tasks. This effort spanned both upgraders and support systems. Through the project, maintenance work expanded significantly due to discovery work from inspections and ill-defined maintenance scopes.

Instrument calibrations

Over 300 calibrations were performed on both the HT and moderator upgraders and support services. These included various field instruments including gauges, switches, transmitters (pressure, temperature, flow, limit, conductivity and level). For many devices, the process instruments were tied into the new DCS control system.

Pipe hanger inspections

Over 200 pipe hanger inspections were performed and adjusted as required.

Diaphragm valves

The refurbishment of over 350 diaphragm valves, ranging in size from 0.5"-6", identified numerous broken valve stems and broken pins that required re-machining, amongst other challenges. Due to the age of materials, identifying suitable spare parts proved a significant challenge. Re-machining of the valve stems was the preferred method of repair as currently available parts were not interchangeable. The Technical Standards and Safety Authority (TSSA) reviewed and approved this method of repair.

Upgrader distributor inspections and tower internals

A preliminary inspection [3] in 2004 of the top eight sections in each tower concluded that the packing was generally in good condition and was wettable. There was some surface discoloration at the points that the water droplets from the distributors first made contact with the packing. However, this was only a small part of the packing surface, and the discoloration did not penetrate beyond the surface. Samples of packing material were removed. Water droplets added to the samples were absorbed and quickly spread through the entire packing sample, indicating good wettability. It was decided not to regenerate the packing. There was still an overall concern that that this qualitative test was not enough to definitively conclude that the packing was in the condition needed to meet the required design performance for throughput and bottom product quality. This would need to be proven during commissioning. Therefore, the condition of the packing was identified as the biggest risk to the project.

Distributor installed in Tower

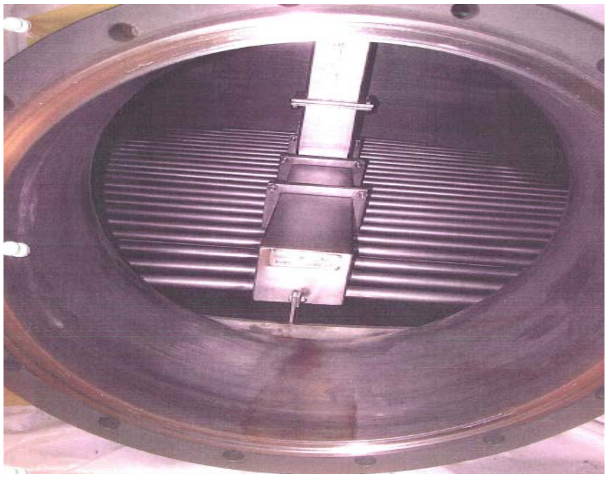
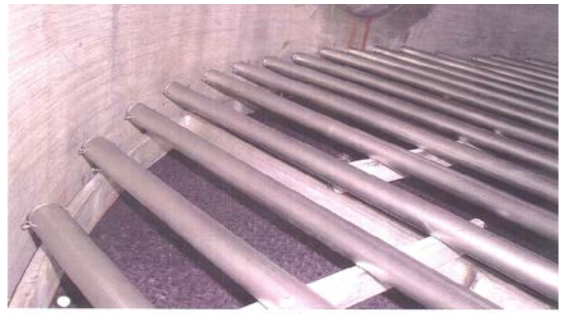


Photo of distributor inside Tower



Tower Packing sits underneath the distributor tubes

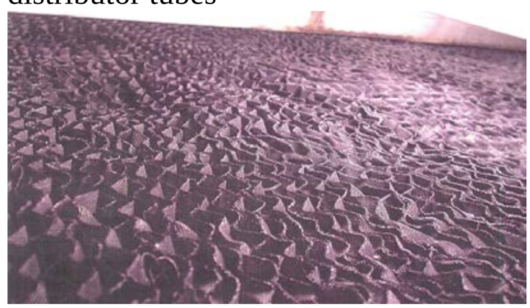


Figure 2 HT Tower Inspections [4]

The majority of the HT tower distributors had pipe cracks, deficient pipe welds and/or deficient support welds. The distributor inspections found that repairs were required to re-tack welds, re-attach tubes to the distributor assembly, and correct bent tubes in both the horizontal, vertical, and radial directions. The interior of the upgrader towers had scratches and tool marks. Rust stains were also identified beneath the sight glasses and inside the man-way channels. All repairs were completed prior to reinstallation of the distributors in the tower. The repairs were expected to increase overall tower performance through better distribution of liquid and vapour through the packing and the towers.

Upgrader heat exchangers

The maintenance program also included the inspection of 17 heat exchangers. The heat exchangers provided the necessary temperature cooling, vapour condensation, or boil-up critical for upgrader operation. In all cases, visual inspection and/or manual cleaning was performed. All upgrader pressure vessels were re-certified with the regulator.

Initial field inspections of the reboiler identified significant fouling on the D_2O process side of the heat exchanger. Mechanical cleaning was not successful in removing the excess scale. Due to the critical operating function of the reboiler, high-pressure water lancing was performed with specialized water-blasting equipment. This successfully removed scale to restore the reboiler heat exchanger tubes surfaces to a clean operating condition.

Figure 3 Fouled Reboiler Tubes before Water Lancing [5]

Upgrader support systems – common service water, chilled water, service water, instrument air, steam/condensate, $D_2$0 cleanup

Maintenance was completed on the upgrader support systems: common service water, chilled water, instrument air, steam & condensate and D20 clean-up systems. This included instrument calibrations (for transmitters, gauges, switches), functional checks of instruments, and inspections on various system components, including valves, and heat exchangers. In numerous cases the inspection of components identified various deficiencies, resulting in components that were either refurbished or replaced in their entirety.

2.2.7 Post-Maintenance Testing

Post-Maintenance Testing (PMT) took place after installation completion sign-offs were obtained to release equipment for testing. During this phase, interaction between Bruce Power and contractor increased significantly with the formation of an integrated team. The integrated team combined the strengths of engineering, installation, operations and maintenance to troubleshoot emerging issues. Step-by-step instructions were outlined in a work coordination plan to demonstrate system functionality, with considerations given to safety, environment, radiation protection, hazards, work protection, etc.

PMT was performed using light water ($H_2$0) in the upgrader system to minimize the radiation risks of working with heavy water ($D_2$0). PMT was completed in a phased approach: first at the component (e.g. pumps) and subsystem (e.g. feed subsystem) level to confirm equipment functionality and subsystem control logic; second, for the entire upgrader system to test overall DCS process control, including response to system upsets and transients. A positive pressure test performed on the upgrader towers successfully confirmed that the towers were leak tight. Baseline vibration and thermography readings were taken for all rotating equipment and electrical equipment. Control valve diagnostics confirmed valve set-up and established baseline performance criteria. PMT confirmed preliminary system testing, proven DCS control and system leak tightness.

Challenges included unavailability of support services (common service water, chilled water, steam). The HT upgrader commissioning was delayed due to leaking components and insufficient flushing of systems. Despite initial flushing of the chilled water system, the field team found considerable debris in the system that required additional flushing and in some cases, removal of equipment for cleaning.

To facilitate quick maintenance for emerging deficiencies, standard work packages were developed for the field maintenance team. Emerging maintenance deficiencies on the upgrader support systems had the most impact in terms of progression through system testing. Despite the exhaustive maintenance program prior to the start of PMT, an additional 300 deficiencies were identified. These deficiencies required component replacement or rebuild, or procurement engineering for equivalent components because the deficient equipment was obsolete.

2.3 Commissioning

The results from commissioning [6] showed that the HT upgrader performance was fully restored, with actual performance far exceeding design [7]. Comparison of design versus actual performance was as follows:

Design: For feed flow 120 kg/h, and feed isotopic 89 wt% D_2O, produce:
bottom product > 99.8 wt% D_2O, conductivity < 0.2 mS/m
head product < 0.3wt% D_2O

Actual: feed flow 141 kg/h, feed isotopic 80.2 wt% D_2O:
bottom product 99.94 wt% D_2O, conductivity 0.12 mS/m
head product 0.008 wt% D_2O

The results also confirmed that tower packing had good separative power, and the poor performance of the HT upgrader prior to shutdown in 1997 was not due to degraded tower packing, but likely from poor boil-up because of a severely fouled reboiler and poor process control. Isotopic profile sampling was performed for the 2 towers while the HT upgrader was operated under steady state conditions. Key process parameters were input into BNGAUG [8], a simulation software program that models the Bruce A upgraders. In order to match the tower isotopic profile generated by simulation to the actual tower profile determined from sampling, the number of theoretical stages (NTS) was varied for the packed sections. The simulation determined there was a total of 691 theoretical stages [9]. Based on the number of theoretical stages per packing section, it was also determined that design performance can be met with 638 theoretical stages. This is less than the calculated 691 stages that the HT upgrader had at the time of vapour profile sampling. From this analysis, it can be concluded that the Bruce A HT upgrader had more than enough separation power to meet performance requirements specified by design. It explains why the HT upgrader exceeded design performance during commissioning. The extra theoretical stages provide a margin for plugging distributors, which reduces the theoretical stages in the affected packed section. It can also be concluded that the poor performance of the HT upgrader before shutdown in 1997 was indeed not due to degraded packing.

Many of the problems that existed before upgrader rehabilitation were resolved:

- upgrader throughput and product quality was restored
- the new DCS reliably controls the upgrader system, with very few upsets that cause the system to either trip to reflux or shutdown, or cause product quality to go out of specification
- all control valves were successfully re-sized and operate in mid range, enhancing system control
- cavitation issues were addressed with the installation of new canned motor pumps. This will reduce the need for frequent pump maintenance.
- The resized new vacuum pumps reliably maintain system vacuum. Air in-leakage through valves, pumps, and gaskets was eliminated. This has improved chemistry and vacuum control.
- replaced systems (new chiller units), repaired and replaced components (valves, field instruments, etc) has significantly reduced system unavailability caused by equipment breakdown

Four major issues still remain to be addressed:

1. Distributor plugging – distributor plugging occurs with the build up of particulate at the distributors that are located above each packed section. As the holes in the distributor become plugged, the water moving down the column is not spread evenly across the packing, causing poor separation of heavy water and light water phases. Upgrader throughput declines over time. Because of partially or fully plugged distributors, the HT upgrader has seen a 40% reduction in throughput after 14 months of operation. The HT upgrader had a forced outage to clean the distributors.

   To address distributor plugging, a new UV oxidation feed pretreatment system was included as part of the Upgrader refurbishment project scope (see Section 5.0). The system was placed in service shortly after the forced outage.

2. Full automatic control by the DCS – although the replacement control system has significantly improved process control and reduced unavailability, it cannot be fully operated in automatic control. Full time operator attendance at the control panel is required.
   During commissioning, steam feed control issues persisted and signal spiking was observed by the DCS, resulting in erratic control valve behavior. Extensive troubleshooting and investigation identified that the existing piping configuration was susceptible to condensate build up. Piping redesign is required.

   Bottom product drawoff could not be controlled automatically. The bottom product is drawn off as a vapour and is controlled by tower 1 sump level. Relatively small changes in level caused a large volume of vapour to be drawn off. This in turn affects the vacuum conditions in the tower, resulting in frequent upsets. A change from vapour drawoff to liquid drawoff, as implemented in the Bruce B HT upgrader, is required to make this control loop operate automatically.

   There is a mismatch in the control components in the feed control loop. The flow transmitter components are incorrectly matched to the feed control valve. A design change is required.
   Finally, the removal from project scope of the on-line heavy water isotopic analyzers has meant the head product drawoff control valve must be operated in manual. The original design of this control loop calls for the valve opening to be automatically controlled by head product isotopic. It was

determined through operating experience at both Bruce A and Bruce B that on-line heavy water analyzers are not required; system response to changing valve opening on head product isotopic is slow, and manual grab sampling is sufficient to control the head product isotopic.

3. Temperature switches - extensive field instrumentation is tied into the DCS with annunciation and/or control inter-locks functionality to monitor control parameters (temperature, pressure, level, etc.). Temperature switches were a particular challenge to commissioning and found to be inappropriate for the application. Due to the large reset range, slow recovery from system upsets resulted in lost production. Different temperature switches are required, with consideration given to re-evaluate set-points and changes to the DCS control program for improved control.

4. Condensate system – the upgrader rehabilitation project focused primarily on the upgrader process and control equipment. During commissioning, there were numerous repairs and replacement of auxiliary system (steam, condensate, common service water, chilled water, air and electrical systems) components. Major scope additions included full replacement of the chilled water units and replacement of numerous field instruments in the steam, air and water systems. The condensate circuit remains a point of vulnerability for reliable upgrader operation. Two new condensate pumps were installed as part of the project. However, because the condensate tank is undersized, the pumps are starting and stopping far too often, causing the pump motor windings to fail. The tank redesign was unresolved during this refurbishment project, and needs to be addressed going forward

3. Moderator Upgrader

3.1 Background

The moderator upgrader is very similar to the HT upgrader. While the two HT towers are essentially the same dimensions (tower 1 & 2 - 44.3 meters high overall and 1.6 meters inside diameter), the two moderator towers differ significantly (tower 1 - 29.3 meters high overall and 1.20 meters inside diameter ; tower 2 - 56 meters high overall and 0.7 meters inside diameter). This difference in configuration allows a high flow rate of high isotopic feed (> 99 wt%) to be fed to tower 1 while simultaneously feeding a lower flow rate of low isotopic (<50 wt%) to tower 2. The purpose of the high isotopic feed stream is to allow on-line upgrading of moderator water taken from an operating unit. Small increases in the isotopic of the moderator such as 0.1 wt% can significantly reduce fuel burnup in the reactor core. The dephlegmator heat exchanger at the top of tower 1 condenses much of the vapour in tower 1 so as to minimize vapour load in tower 2. Reducing the diameter of tower 2 lowers the cost of the tower. A small diameter tower can be used because the feed rate of downgraded moderator water is low; smaller amounts of low isotopic moderator water is collected compared to the relatively high amounts collected from the heat transport system.

3.2 Design and Implementation

The overall maintenance and modifications for the HT upgrader were similarly performed on the moderator upgrader. Due to the need to bring into service the HT upgrader as quickly as possible, the moderator upgrader tower distributor inspections did not take place until the HT upgrader was returned to service in November 2009. To decrease radiation fields to within acceptable limits, the moderator upgrader had to be flushed with light water (H_20) to remove heavy water (D_20), which was never drained during lay-up. During the moderator towers distributor inspections, it was noted that the overall condition of the tower internals was much cleaner than the HT towers. As with the HT towers, all distributors were cleaned and repairs were made to tower internals.

3.3 Commissioning

The moderator upgrader was successfully demonstrated to process low isotopic downgraded moderator water (35 – 50 wt%) at a the design feed rate of 25kg/h. Bottom product had isotopic greater than 99.97 wt%, and head product was less than 0.03 wt% [10], exceeding performance specifications of greater than 99.9 wt% isotopic for bottom product and less than 0.1 wt% for head product [11].

Similarly, on-line processing of high isotopic moderator water was successfully demonstrated. Heavy water with isotopic of 99.77 wt% was fed to tower 1 at a rate of 220kg/hr. Bottom product had 99.97 wt% isotopic, compared to the design requirement of 99.86 wt% , and head product had isotopic of 0.005 wt%, compared to the design requirement of < 0.1 wt% isotopic.

The moderator upgrader did not have a history of distributor plugging. It did not have the reboiler fouling as seen in the HT upgrader. The moderator upgrader had the same major control and instrumentation and condensate system issues as that encountered with the HT upgrader. Refer to Section 2.3

4. Upgrader Instrumentation and Control

4.1 Background

The original analog control panels that controlled the HT and moderator upgrader systems (two control panels – one for HT and one for moderator) were supplied by Fischer and Porter (F&P) to Ontario Hydro around 1977 through the upgrader designer and supplier Sulzer Canada. The panel mounted instruments were 1970's technology that was used throughout the Bruce station at that time on both local panels such as the upgrader and in the Main Control Room. These instruments were the F&P front of panel analog controllers, analog indicators, strip chart recorders and back of panel instruments such as alarm modules. These devices formed the basis for the upgrader process control loops; the upgrader interlock and shutdown logic was carried out by a separate relay cabinet that was common practice for that period.

Control loop field instrumentation was typically Fisher control valves interfacing with F&P pressure, level and flow transmitters. A typical loop configuration consisted of an F&P two-wire field transmitter with a 4-20 mA DC signal to both the back of panel alarm module (for analog low and high warning alarms) and front of panel controller (and recorder if trending was required). The 4-20 mA DC controller output to the Fisher control valve went to a current to pneumatic (I/P) transmitter on the valve. The control valves also included solenoid valves and limit switches. The solenoid valve in the air line interfaced with the relay shutdown logic to put the valve into its failsafe position. There were also typical pressure, level and flow switches that interfaced with shutdown relay logic as low-low and high-high shutdown alarms.

While this analog control system functioned for over 20 years, it became increasingly difficult for Ontario Power Generation (OPG) to find spare parts. But a more critical concern was the poor performance of some of the control loops and the inability to gather real time data and historical process trending. This contributed to a gradual decrease in upgrader performance and the inability of the upgrader to reach production targets. Bruce Power therefore recognized that a planned life extension project of the Bruce A Unit 1 and 2 reactors mandated the inclusion of a modern upgrader control system [12].

4.2 Design and Implementation

4.2.1 Hardware

An overview of the control configuration is shown in Figure 4. The upgrader controls consist of an Emerson Delta V DCS. The DCS is used to monitor and control each upgrader. The DCS hardware was installed in marshalling termination, power supply and control hardware cabinets. The DCS equipment for the HT and moderator upgraders was broken down as follows: terminal blocks for field wiring in the marshalling cabinets; redundant controllers, analog input (AI) and analog output (AO) cards, digital input (DI) and digital output (DO) cards and communication hardware located in a control hardware cabinet, and power supplies are in the power supply cabinet which is common to both upgraders control system.

The Emerson Delta V system from Lakeside Controls was chosen as the supplier for the DCS. One critical issue was Lakeside's ability to do a complete system simulation at their shop, including all process control and shutdown logic. Sulzer Canada had worked with Lakeside to develop a simulator on the Qinshan upgrader DCS, so the simulator could be modified for the Bruce upgrader. This Factory Acceptance Test was carried out by SNC Lavalin-Aecon and witnessed by Bruce Power Operations.

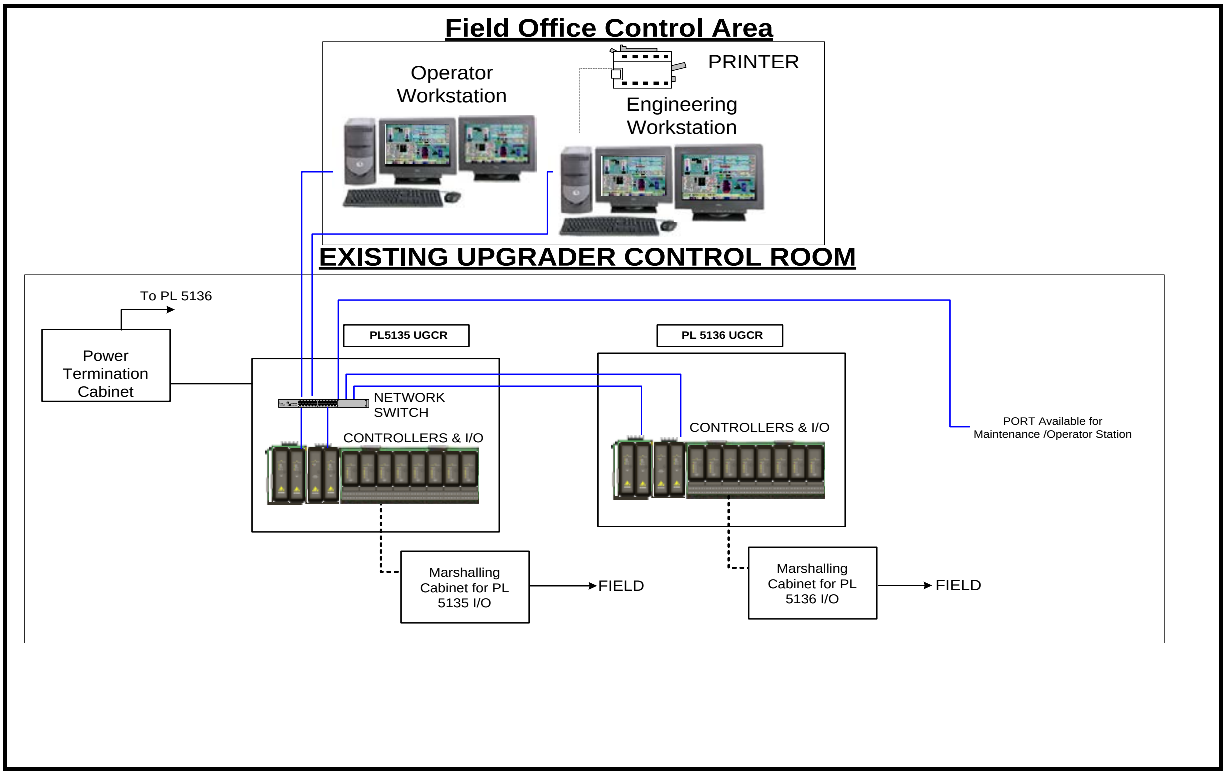


Figure 4 Schematic of Distributed Control Architecture

In addition to meeting all of the Bruce Power design requirements, Lakeside had the advantage of being able to supply the seventeen replacement control valves and eight pressure/flow transmitters. Lakeside also assisted in evaluating the control valve sizing and stability issues. This overall responsibility for all control loop hardware provided total loop integration in terms of commissioning, operation and maintenance. As Lakeside was also the DCS vendor for the Qinshan upgrader, they understood the Sulzer upgrader process and nuclear industry Quality Assurance and Human Factors requirements.

Also, the Delta V DCS utilized HART communication protocol for the 4-20 mA lines and could provide historical data to Bruce Power's Pi information management system. Hardware to make the connection to the Bruce Power LAN was provided but not implemented at the time of commissioning.

4.2.2 Legacy documentation

Another challenge was upgrading and translating Sulzer's process and logic control design documentation to current standards for not only Bruce Power but also Lakeside controls. The Bruce A upgrader was Sulzer's second generation of design (Pickering in the 1960's was the first) and the design documentation provided by Sulzer for Bruce A was still evolving and did not meet current standards. All the original documentation (design manual, operating manual, control and logic diagram, interlocking diagram, instrument and control valve data sheets) needed significant revision.

Furthermore, additional documentation had to be provided to the DCS vendor (input/output lists, hardware specs, hardware layout, human factors requirements of the HMI, connection wiring diagrams etc.) that was not part of the original Sulzer design package.

4.2.3 Tying in the new Delta V DCS

Due to the above issues, there were many details that could not be documented until the new system was connected and powered up. Any new information was incorporated into the designs using field changes to ensure that construction could continue. For example, even though great care was taken to accommodate cables that were too short to reach the new DCS marshalling cabinets, some cables needed to be replaced because they were not long enough or damaged. Large marshalling panels were installed above the upgrader control room with spare capacity for future installations.

4.3 Commissioning and Operating Experience

4.3.1 Commissioning methodology

Prior to the live commissioning, a number of pre-commissioning checks were performed to allow the actual commissioning process to move quicker. All wires were checked point to point and ground to ensure that the field devices were connected to the correct input/output (I/O) cards on the Delta V system. The logic circuits were energized and a "logic check" was performed to see if the signal received at the DCS made logical sense given the upgraders state. This ruled out small logic errors such as being connected to the wrong set of contacts on a field device or broken or shorted cables. A third check was done to verify the new DCS alarms by simulating the signal to bring in the alarm by shorting a set of contacts, or introducing a 4-20mA signal.

4.3.2 Commissioning challenges

There were two main types of challenges that occurred during commissioning; issues that arose from equipment that was not replaced and issues due to equipment that was too "smart" for the application.

Some equipment that was auxiliary to the upgraders was not in scope to replace during this refurbishment. Interfacing modern control equipment to older discreet logic circuitry presented some challenges during the design stage which resulted in multiple changes during construction. Additional changes were required once the upgrader became live and the behavior of the logic could be observed. Components not replaced functioned inconsistently, which made the trouble shooting process difficult. Spare parts or like for like replacement parts were also not available (one of the main reasons for the refurbishment).

- The HT and moderator downgraded D_2O feed flow transmitters were unique compared to the new flow transmitters because they required their own DC power supply. The old power supplies were discarded when the old analog control system was removed and it was late into construction before it was discovered that power supplies needed to be purchased. The transmitters behaved inconsistently due to their age and frequent fouling of small lines within the instrument. The consequence of this inconsistent behavior was that the feed control for the evaporators on both HT and moderator systems could not be controlled in automatic mode.

- The logic which controlled a pair of pumps to empty the steam condensate tanks was also left original. While it did not cause issues during construction, commissioning was difficult due to aged limit switches, difficult to understand discreet logic and inconsistent pump behavior. Replacing the level indication and allowing the DCS to control the pumps would have been an easy way to modify the pump behavior if the need arose.

- The old refrigeration units were replaced with modern units. However, the old discreet logic and annunciation panel that interfaced the chillers with the new DCS was left installed. This caused confusion during construction and difficulty for the design team and the vendor supplying the system. The controls on the new chillers should have been interfaced directly with the new DCS to avoid these challenges.

Another difficult aspect of the design was integrating equipment that was “smart” to the modern DCS. Most modern equipment comes with its own set of controls and software features. These features were not required on the individual equipment due to the power of the Delta V DCS, and in some cases prevented proper function with the new DCS. The new weigh scales that measured the upgraded D2O, the chilled water refrigeration units and the UV oxidation system all came with their own modern control hardware. Due to the features and redundancy of the DCS, it would have been more efficient to replace the old analog equipment with simple modern hardware and allow the DCS to control these systems. Each of the above systems required multiple changes during commissioning to allow them to work correctly with the DCS.

4.3.3 Commissioning results

Some limitations encountered during commissioning such as the existing piping configuration, auxiliary hardware not being replaced and control valve plug selection prevented the system from running in full automatic control. However, each system easily met the design throughput with the control valves operating close to the middle of their full range. Due to the response of the modern DCS, the output of the upgrader could be increased. Additional hardware changes are required to realize higher output.

5. Ultraviolet (UV) Oxidation System

5.1 Background

Before shutdown in 1997, the HT upgrader experienced a forced shutdown every 12 – 14 months due to plugging of the distributor holes [1]. The plugging phenomenon occurred at such a rate that half of the 32 distributors plugged in less than a year. During this time, the upgrader feed rate reduced from 120 kg/h to less than 60kg/h. A 6 - 8 week outage followed, with each distributor disassembled and removed from the tower, then manually cleaned and reassembled inside the tower. The moderator upgrader did not experience distributor plugging and forced shutdowns.

Studies have pointed to organics in the upgrader feed stream as the major contributor to distributor plugging [13, 14]. High levels (1 – 20 mg/kg) of dissolved organics in the feed stream, and the breakdown of these compounds into organic acids caused the water in the towers to become acidic. The acidic water removed copper from the packing and the copper oxide deposited at the distributor holes. This eventually resulted in plugging of the distributor holes. The source of the organics was believed to be volatile organics that were captured, along with the heavy water/light water vapour, by the vapour recovery desiccant in the dryers. Hydrophobic organics in the downgraded "dirty" water are removed by the carbon and strong base anion resin in the ion exchange (IX) columns of the cleanup system. However, low molecular weight polar organics such as acetone and methanol are hydrophilic and cannot be easily removed by carbon and IX resin.

A total organic carbon (TOC) specification of less than 1 mg/kg in the upgrader feed was recommended. Because the TOC level of less than 1 mg/kg could not be consistently achieved with the ion exchange based cleanup system, a TOC specification of less than 3 mg/kg for upgrader feed was adopted. At Ontario Power Generation's Darlington facility, a heavy water cleanup system with a UV oxidation system utilizing hydrogen peroxide has consistently been able to reduce TOC levels to less than 1 mg/kg. The reaction of UV light with hydrogen peroxide (introduced in the "dirty" water) generates hydroxyl radicals (•OH). The •OH radical is highly reactive and can oxidize organic molecules to carbon dioxide and water. Based on the Darlington experience, a UV oxidation system utilizing hydrogen peroxide was installed as part of the scope of the Bruce A upgrader rehabilitation project.

5.2 Design and Installation

The design requirements were as follows [15]:

TOC in the downgraded "dirty" water	40 mg/kg
TOC in the water following UV-peroxide treatment	< 0.5 mg/kg
Residual hydrogen peroxide in the treated water	< 1.0 mg/kg
Processing rate of 20,000 liters of downgraded "dirty water through the UV-peroxide system	< 24 hrs

A peroxide specification of < 1 mg/kg in the treated water was necessary to prevent residual peroxide from attacking the tower packing, as well as fouling of the ion exchange resin in the cleanup system. Following treatment of the downgraded "dirty" water by the UV-peroxide system, the water would need to be passed through the existing ion exchange columns to remove inorganic ions created by the destruction of organic molecules. The final treated water must have conductivity < 0.1 mS/m. The processing rate was based on ensuring that the combined processing steps required by the UV-peroxide unit and ion exchange cleanup system did not cause the HT upgrader to go on reflux from lack of downgraded "clean" feed.

Prior to equipment design, testing with simulated solutions was conducted by the equipment supplier, Calgon Inc., at their facilities [16]. The simulated solutions consisted of methanol, ethanol, iso-propanol and acetone of equal concentration by weight, with a final TOC concentration of 40 mg/kg. 25 L batch solutions were charged with hydrogen peroxide concentration of 300 mg/kg. After passing through a 1 kW pilot lamp with a UV light having a frequency range of 200 – 260 nm, both the TOC and hydrogen peroxide in the effluent was reduced to less than 0.5 mg/kg. Based on data collected from these tests, it was determined that two reactors in series, each containing a 30kW UV lamp, would be able to reduce the TOC and hydrogen peroxide to less than 0.5 mg/kg.

Approval was received from the CNSC to classify the UV oxidation system as CSA-N285.0 – Class 6 on the basis that the unit will only process HT water, which will always have tritium content less than 10 Ci/kg. The terminal points at the process inlet and outlet that connects to the existing cleanup system piping will have nuclear class 3 valves because the existing cleanup system and piping is classified as a nuclear class 3 system.

Figure 5 shows a schematic of the UV cleanup system. The initial design for treatment involved four separate flow configuration as follows:

- A 20,000 L tank containing downgraded "dirty" water is recirculated through the existing cleanup system consisting of one 7 ft^3 column containing activated carbon, and three 7 ft^3 columns in series, each containing ion exchange resin. This removes radioactive particulates and ionic species that could plate out on the UV skid components.

- The 20,000 L of downgraded "dirty" water is then pumped to the UV-peroxide unit to another empty downgraded "dirty" water tank. Pumping rate is 1.1 L/sec. A flow transmitter on the line is interlocked to shut down the UV lamps in the reactors to prevent overheating of the fluid in the reactors. When flow to the UV skid is initiated, a metering pump is started up to deliver 50 wt% hydrogen peroxide (H_2O_2) at a rate 2.3 L/h for 5 hours to the piping upstream of the first UV reactor. This corresponds to 300 mg/kg of H_2O_2 in the feed stream. The effluent of the first UV reactor then enters the second reactor. Each reactor has a 30kW UV lamp to aid in the destruction of organics. The effluent from the second UV reactor passes through a heat exchanger to remove heat in the water from the UV lamps.

- The effluent from the UV skid is recycled back to the downgraded "dirty" feed tank without H_2O_2 addition, but with the UV lamps on. This recycle flow continues for at least 24 hours, by which time residual peroxide in the downgraded water is removed as it passes through the UV reactors.

- After treatment through the UV-peroxide unit, the treated water is again processed through the existing cleanup system. This removes inorganic carbon species created from the destruction of organics.

The four passes need to be completed within one week for each 20,000 L downgraded storage tank in order to keep up with HT upgrader feed rate of 120 kg/hr.

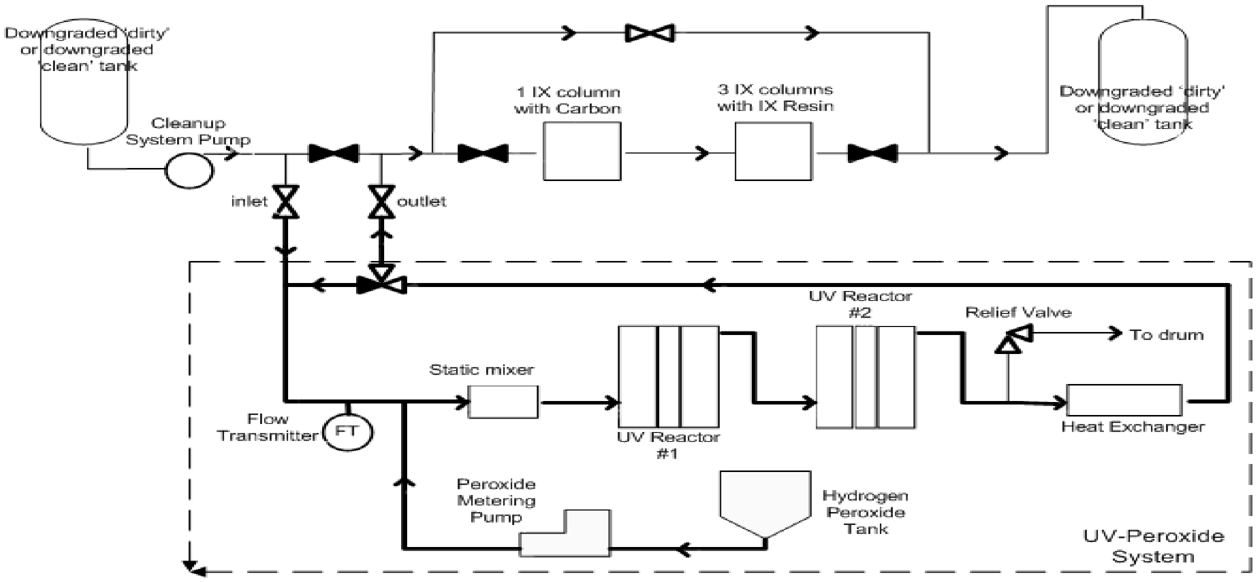


Figure 5 Schematic of UV-Peroxide Cleanup System

5.3 Commissioning and Operating Experience

5.3.1 Process configuration and results

The initial three pass configuration was a starting point for testing. However, numerous alignments are available:

- recycle water through the IX system or UV system using the same “dirty” tank
- recycle water through the IX system or UV system using the same “clean” tank
- process water from “dirty” tank to a different “dirty” tank through the IX or UV system
- process water from “dirty” tank to “clean” tank through the IX or UV system
- process water from “clean” tank to a different “clean” tank through the IX or UV system

The primary determinant of configurations used is availability of tank space and processing time. It is preferred that a standard configuration is established, rather than having a different confirmation for each treatment, so that a standard procedure is used. Table 1 shows the results using the new UV oxidation process and the previously used IX treatment (17).

Table 1 Results of UV Oxidation and IX Treatment

	Specification	Results

TOC, mg/kg	< 0.5	0.1 – 0.5
Peroxide, mg/kg	< 1	0 – 0.5
Conductivity, mS/m	< 0.1	< 0.1
Total treatment time, days	7	5 – 10

Because the main determinant of process configuration is to ensure the maximum amount of empty space is made available in five “dirty” tanks (20,000 L capacity each), other configurations were tested. This space is needed in case there are high leak rates from operating units, or there is unavailability of the cleanup system or the HT upgrader, resulting in buildup of downgraded “dirty” water. To make maximum space available in the “dirty” tanks, as much processing as possible should take place using the four “clean” tanks (10,000 L capacity). Although variations are possible, the current standard configuration involves four passes:

- Process 10,000 L with a single pass through the IX system from “dirty” tank to a “clean tank” (1 day). This removes radioactive particulates and ions.
- Process 10,000 L with a single pass through the UV system from “clean” tank to another receiving “clean” tank (approximately 5 hours). Peroxide injection takes place during the entire pass. This brings TOC < 0.5 mg/kg. However there can still be high residual peroxide in the treated water.
- Process 10,000 L with a single pass through the UV system with no peroxide and with only the UV lamps on from “clean” tank to another “clean” tank. This removes residual peroxide to < 0.5 mg/kg (reminder of day). However higher amount of residual peroxide can sometimes be present
- Recirculate 10,000 L through the IX system (1 – 2 days). This brings conductivity < 0.1 mS/m, and ensures residual peroxide < 0.5 mg/kg.

5.3.2 Major issues that were encountered during commissioning and operation

The combination of IX and UV-peroxide treatment resulted in producing “clean” water that consistently met upgrader feed specifications. However, several major issues were encountered, as follows:

1. **Process:** The total processing time to treat 20,000 L frequently exceeded 7 days. The ability to cleanup water becomes important if collection rates are high. The first and second passes in the current configuration can be combined if an optional takeoff point is made at the exit of the IX cleanup system. Currently, the takeoff points are before the IX cleanup system. This change will require a modification to the UV system that allows an internal recycle flow inside the UV system (see (2) below) so that the low flow permissive does not shut down the UV lamps. Additional work in optimizing peroxide addition to the level of organics can reduce the need for the third pass. Software programs such as the AdOx program from the University of Michigan can match the level of organics with hydrogen peroxide. An optimized level of hydrogen peroxide can result in both TOC and peroxide levels at less than 0.5 mg/kg after one pass through the UV system.

2. **Controls:** lower than expected flow from the cleanup system pump resulted in frequent shutdown of the UV lamps. A low flow set point was lowered to the minimum level allowed by the

manufacturer. However, this will result in hotter temperature inside the UV reactors, resulting in faster breakdown of the seals (resulting in heavy water leaks), more frequent lifting of the relief valve, and lower life of the UV lamps. A partial recycle with a manual flow control valve from the exit of the UV unit back to the inlet line would allow for higher flow through the unit.

3. **Peroxide Delivery:** the long delivery line from an existing hydrogen peroxide tank to the UV skid has resulted in long delays for peroxide addition because the injection line was not fully primed. Operating procedures currently ensure the pump is properly functioning and the line is fully primed before startup of the UV unit. Leaks at various components have caused unavailability. A future unit, as planned for the Bruce B station, should be designed with the hydrogen peroxide tank next to the UV system.

4. **UV Reactors:** the seals on the UV reactors degrade due to exposure to the strong UV light. This has resulted in heavy water leaks and high airborne tritium. In addition, the UV lamps have required frequent change out because of their high use and limited life. Leaks and frequent lamp changes has resulted in high unavailability of the UV system. Both UV reactors have high and low lamp settings, and are currently operated at the high lamp setting. Performance testing would need to be done using the low lamps settings. If successful, this would reduce the degradation of the reactor seals and improve lamp life.

5. **Safety:** when the UV lights are first turned on during startup, it takes a few minutes before the blowers for the UV reactor to start up. During this time, high levels of airborne ozone are measured around the reactors. The ozone then dissipates. A tent is temporarily enclosing the UV system. Operators are not allowed in the tent during startup. A permanent enclosure is required.

   The relief valve at the exit of the second UV reactor has lifted on occasion. The tritiated water from the relief valve is discharged into a drum with a 2” hole. For overpressure protection reasons, this hole cannot be fully sealed. Vapours from the drum have resulted in high airborne tritium. Redesign of the discharge path to another vessel other than a drum will eliminate the airborne tritium hazard. The temporary tent currently enclosing the UV oxidation system has minimized the airborne tritium hazard.

6. **Resin Consumption**: the breakdown of organic compounds to inorganic compounds as it passes through the UV reactors results in ionic compounds that must be removed by ion exchange in order to meet the conductivity specification for upgrader feed. As a result ion exchange resin consumption in the IX cleanup system has doubled.

5.3.3 Effect on HT upgrader distributor plugging

Due to delays in procurement and installation of the UV system, the HT upgrader was started up without the UV oxidation system. Without the UV oxidation system, the distributors plugged and feed flow reduced to < 70 kg/h after 14 months of operation. This followed the same experience before the upgrader shutdown in 1997. A 4 week outage took place to clean the distributors. The UV oxidation system was placed in service shortly after the outage. There has been no distributor plugging, and feed flow has been maintained constant at 120 – 130 kg/hr for 17 months of operation following this outage. Preliminary results of the UV-peroxide system indicate that it has been successful in preventing early distributor plugging. Data continues to be collected.

6. Conclusions

The improvements to the HT and moderator upgrader have resulted in successful return to service of both upgraders. Both upgraders have now operated for over 2 years and have exceeded design performance for throughput and bottom product quality. Poor performance (low throughput, and low product quality) of the HT upgrader prior top shutdown in 1997 was due to severe fouling of reboiler, rather than poor condition of packing. The extensive modifications and maintenance to both upgraders has significantly improved availability. The condensate system pumps remain a single point of vulnerability. The upgrade from a hard wired control system to a DCS has resulted in more consistent control of process parameters. The addition of a UV oxidation system has prevented early plugging of the HT upgrader distributors.

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