THE PRIMARY HEAT TRANSPORT SYSTEM VACUUM DRYING OF A CANDU POWER PLANT

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ABSTRACT

Existing CANDU reactors were designed for a service life of up to 55 years. After about 25 years of operation, a CANDU power plant needs to be refurbished to extend its service life for another 25 to 30 years. As part of the Bruce Power Units 1 and 2 Restart Project, one major work scope is the fuel channels replacement. To facilitate this refurbishment initiative, the Primary Heat Transport (PHT) system is required to be drained of all heavy water (D_2O) and a functional dry state must be achieved. However, after the PHT system is drained, a significant quantity of D_2O still remains in the fuel channels, pre-heaters, and other low-lying portions of the PHT and Feed and Bleed (F&B) system. The residual D_2O in the PHT and F&B systems is required to be removed and recovered to allow for adequate drying and to minimize the potential for radiological releases.

The purpose of this paper is to describe the method used to dry the PHT system at Bruce A Nuclear Generating Station, Unit 1. The method used for the drying process is termed "vacuum drying" in which trapped D_2O is boiled off through the combined application of heat addition to the PHT system under near vacuum conditions, such that the boiling point of D_2O is reduced by lowering the pressure within the isolated PHT system. Proper isolation of the PHT system is critical for preventing air ingress and maintaining the vacuum conditions. Sufficient heat is required to be added to various locations suspected of containing significant quantities of D_2O, in order to raise the D_2O temperatures to allow an increased boiling rate of D_2O within the PHT system. A vacuum drying process system was designed to evacuate the isolated PHT system and draw D_2O vapour, re-condense the vapour, collect the condensate, transfer the collected condensate to the station D_2O collection system, and purge non-condensed vapour and gases to the station vapour recovery system.

1 INTRODUCTION

Vacuum drying is a process used to remove liquid material from a solution or mixture under reduced air pressure, which results in drying at a lower temperature than is required at full pressure. Vacuum drying is considered to be a clean, fast, cost effective, and efficient drying process accepted by most industries.

The boiling point of light water (H_2O) lowers as the atmospheric pressure reduces. Similar to light water, the boiling point of heavy water (D_2O) also lowers as the atmospheric pressure reduces. Light water boils at 100°C at an atmospheric pressure (sea level). Heavy water boils at 101.42°C at an atmospheric pressure and boils at 26.5°C at -97 kPa (g). During a vacuum drying operation, the pressure within a closed system is reduced to near vacuum conditions to allow the water to vaporize at relative low temperature. Heat may be added to promote the vaporization.

Vacuum drying has comparable advantages to other drying processes and could be applied to where conventional drying cannot be used. Specially, its application in the nuclear industry has significant advantages in preventing radiological hazards.

The nuclear industry has been applying vacuum drying for different process purposes. Many systems and equipment in nuclear power plants contain radioactive fluid. To execute the maintanitence and repair work, these systems and equipment must be evacuated of all residual radiological hazards. Vacuum drying can meet these needs effectively and facilitate the work such that radiological hazards are minimized, thereby reducing dose and costs.

2 APPLICATION IN A CANDU NUCLEAR POWER PLANT

The CANDU reactor is a fuel tube type reactor. The fuel bundles are installed in hundreds pressures tubes (*i.e.*, fuel channels) which constitute part of the PHT system. The PHT system generally includes circulating pumps, inlet and outlet headers, fuel channels, feeder pipes to and from each fuel channel, and the primary side of steam generators and pre-heaters. A pressurizer connected to the east outlet header provides pressure control to the PHT system. The PHT system circulates pressurized heavy water through the fuel channels, thereby removing the heat produced in the fuel. The heat is then transferred to light water in the steam generators (*i.e.*, boilers). A CANDU nuclear power plant requires refurbishment after about 25 years of operation. The fuel channels are the major components to be replaced during plant refurbishment.

The PHT and Feed and Bleed systems can be considered as a large closed vessel containing entrapped D_2O, particularly in the sagged pressure tubes in the core and in the ‘U’ tube bundles of the pre-heaters. Based on the scope of the plant refurbishment, the PHT system could be drained and dried partially or entirely to facilitate the equipment and component replacements in the applicable systems.

Vacuum drying has extensive applications in a CANDU nuclear power plant. The application has been used in spent fuel storage facilities to dry spent fuel for long-term storage and was also utilized to dry the Annulus Gas System. Vacuum drying has been used to successfully dry the Primary Heat Transport system of CANDU plants to facilitate large scale fuel channel replacement. The technology was used successfully at Pickering, Bruce B, Bruce A Unit 2 and was chosen as the most feasible method to remove the remaining D_2O in the PHT system at Bruce A Unit 1.

3 THE PHT SYSTEM VACUUM DRYING PROCESS

Prior to the commencement of fuel channel replacement, the PHT system must be completely drained and dried to minimize the potential for radiological releases that could endanger personnel performing the refurbishment scopes of work. After the PHT system is drained, there are still significant amount of D_2O trapped in the system. The trapped D_2O must be removed to ensure that the PHT system has relatively dry conditions.

A temporary vacuum drying process system is employed to dry the PHT system. The vacuum drying process consists of three sub-processes. First, the PHT system needs to be isolated to prevent air ingress and to protect equipment which cannot withstand the vacuum conditions. This is necessary to establish a PHT system vacuum drying envelope. Next, the heat addition process provides heat to selected locations that must be raised in temperature to aid the vaporization of D_2O. Finally, a vacuum process system which includes the vacuum pumps and vapour process equipment is needed to lower the pressure and draw the vapour out of the PHT system.

The PHT system vacuum drying process shall not have any impact on nuclear safety as the PHT system will be de-fueled and drained to the extent practical prior to the application of the drying process. The main concern with this process is the handling of tritiated heavy water from the PHT system and the potential for leaks and/or spills from the system during the drying process. The temporary modified piping configurations will be removed at the end of the operation and the systems will be restored to its original configuration prior to the return to service of the respective systems.

3.1 The PHT System Vacuum Drying Envelope

Before vacuum drying commences, an envelope is established to provide a vacuum tight seal to allow the PHT system to depressurize and to maximize vacuum pump efficiency. Within the sealed envelope, the overall air leakage ingress can be minimized such that the pressure can be reduced to -97 kPa (g) nominally. To achieve this, the portions of the PHT system which have been previously drained, and other portions of the PHT system which either cannot withstand vacuum conditions or are known to be sources of air ingress, need to be adequately isolated.

Vacuum Drying Envelope Isolation

Depending on the scope of the drying process and the system configurations, the drying envelope could be the lower portion of the PHT system which includes: headers, fuel channels, and feeder pipes to and from each fuel channel. In addition, this envelope may extend to the upper portion of the PHT system including: circulating pumps, and the primary side of steam generators and pre-heaters. Some portions of the Maintenance Cooling System and the Feed and Bleed System could be included within the envelope.

Depending on the defined vacuum drying envelope, the PHT system can be isolated from its interfacing systems which can potentially be either the source of air ingress or are sensitive to vacuum conditions. A vacuum drying envelope will be established by closing the selected valves and/or cutting and capping of piping where valve positioning is not applicable. The valves to be closed and cut/cap locations are selectively chosen based on the plant system configurations and operating procedures.

Equipment and Components Assessment under Vacuum

The equipment and components within the vacuum drying envelope must be assessed under vacuum conditions. Stress under external pressure for large vessels, such as steam generators, pre-heaters, bleed condenser, bleed cooler, and pressurizer, are required to be evaluated. Some segments of the larger pipes also need to be assessed. An engineering assessment is required to be prepared in order to demonstrate that all the vessels and pipes within the vacuum drying envelope are capable of withstanding the expected vacuum conditions.

Overpressure Protection of the Vacuum Drying Envelope

During the vacuum drying operation, the reactor is in the Defuelled Guaranteed Shutdown State and there is no energy source to create positive pressure in the system. For conservative considerations, a relief valve with a 15 psig set point was installed on the bleed condenser to ensure that the pressure within the vacuum drying envelope would not exceed 15 psig.

3.2 Heat Addition to the Vacuum Drying Envelope

The method used for drying the PHT system applies a combination of heat addition to the PHT system and reducing the boiling point of D_2O by lowering the pressure to near vacuum conditions. The addition of heat to the PHT system will provide sufficient heat to raise the D_2O temperatures to between 60° C and 80° C to allow for an increased boiling rate of D_2O within the PHT system. To achieve this, heat will be added to various locations within the PHT system which are known or suspected of containing significant quantities of D_2O which cannot be drained by conventional means.

Heat Addition Locations

The fuel channels and the pre-heaters are considered to have a large amount of trapped D_2O. The sufficient heat energy must be applied to them to achieve sustained boiling. The other critical locations of heat addition include: feeder cabinets, end fittings, bleed condenser, bleed cooler, pressurizer, various large valve bodies and large pipe segments within the PHT system, and auxiliary rooms containing small bore piping and instrument lines.

PHT System Heat Up

The selected locations within the PHT vacuum drying envelope will be heated by various means, and heat will be transferred across the PHT system pressure boundary to raise the temperature of D_2O to the desired temperatures. The temperature will be increased as much as practical to promote vaporization of D_2O. These heating means with their controls will minimize the impact to the PHT system. The heat energy sources provide heat to the PHT system without modifying the pressure boundary of the PHT system and do not have any adverse impact on the PHT system loads and load combinations.

3.3 Vacuum Drying Process System

A Vacuum Drying Process System was employed to decrease the pressure in the PHT system to draw a vacuum to allow for D_2O to evaporate at lower temperatures. The vapour will be drawn by the vacuum pump through this system to be recondensed and collected. Non-condensed vapour and gases will be directed to the station vapour recovery system.

Design Concept

The PHT vacuum drying process system typically consists of vacuum pumps, D_2O vapour condenser, pump exhaust coolers, D_2O condensate collection tanks, and a process system for non-condensed gases. The vacuum drying process system will be temporarily installed within the Reactor Auxiliary Bay and attached to the PHT system. The majority of D_2O vapour will be drawn across the D_2O vapour condenser where it will be cooled and condensed. The remaining vapour drawn from the system will be condensed by the pump exhaust coolers. The D_2O condensate from the D_2O vapour condenser and the exhaust coolers will be collected in the D_2O condensate collection tanks. The D_2O condensate will then be pumped from the tanks via a filter into the station D_2O Collection System. The non-condensed vapour and gases will be directed to the Confinement D_2O Vapour Recovery System. The Low Pressure Service Water System will supply the cooling water to the D_2O vapour condenser, the vacuum pumps, and the exhaust coolers.

4 BRUCE A UNIT 1 PHT SYSTEM VACUUM DRYING

4.1 Introduction

Bruce A Nuclear Generating Station was shutdown and laid up in 1996. Units 3 and 4 returned to service in 2001. Bruce Power decided to return Units 1 and 2 back to service and the Bruce A Restart Project started in October 2005. One of the major tasks of this refurbishment project is to replace the fuel channels.

The PHT system of Unit 2 was drained and dried in 1996 when the unit was laid up. The PHT system of Unit 1 was not drained and dried. As part of the Bruce A Restart Project, the Unit 1 PHT system was drained in early 2007. A significant amount of heavy water was still trapped in the PHT system and portions of the Feed and Bleed system. Therefore, a vacuum drying process operation was applied to dry the PHT system and its auxiliaries between July 3, 2007 and August 22, 2007.

4.2 Bruce A Unit 1 PHT Vacuum Drying Envelope

CANDU nuclear power plants have been evolving since the first CANDU reactor was constructed. There are differences among CANDU reactor power plants built over the years. Specifically, boiler and pump isolation valves do not exist in the heat transport system at Bruce A. This increases the relative volume that must be evacuated in Bruce A. The calandria is surrounded by an external shield tank in Bruce A. This will be an additional heat sink for heat addition to the calandria. Moreover, the pre-heaters in Bruce A are external and cannot be isolated from the heat transport system.

Based on the configuration of the PHT system at Bruce A Unit 1, the vacuum drying envelope consists of fuel channels, six headers, feeder pipes to and from each fuel channel, four circulating pumps, the primary side of eight steam generators and four pre-heaters. Some portions of the Maintenance Cooling System and the Feed and Bleed System including the pressurizer, bleed condenser, bleed cooler and feed pumps and their associated piping are also included.

Most of the PHT interfacing systems were isolated from the PHT vacuum drying envelope by temporary valve positioning (*i.e.*, closing). These systems are either PHT auxiliary systems or instrumentation control systems. Typically, the following systems are included:

- Emergency Coolant Injection System
- PHT Feed, Bleed & Relief System
- PHT Storage, Transfer, and Recovery System
- PHT Purification System
- PHT D_2/H_2 Addition System
- PHT D_2O Collection System
- Maintenance Cooling System
- Heavy Water Sampling System
- Instrument Air System
- Channel Power Measurements
- PHT Primary Pressure Control
- SDS1/SDS2 Measurements and Trip Control

The following systems contained components and vessels that could not be isolated by closing valves, and therefore were isolated from the PHT vacuum drying envelope using manual cutting and pressure boundary capping of pipes:

- PHT D_2O Collection System
- Heavy Water Sampling System
- Heavy Water Transfer System
- PHT Storage, Transfer, and Recovery System
- PHT Feed, Bleed & Relief System

It was expected that the aged steam generator tube bundles with cracks would be the significant source of air leakage. Custom boiler bungs were designed and installed on the inlet/outlet of boilers nozzles as a precautionary measure.

4.3 Bruce A Unit 1 PHT Vacuum Drying Heat Process

Within the PHT vacuum drying envelope, various heat sources were chosen or designed to add heat to various locations including: fuel channels, feeder cabinets, pre-heaters, valve bodies and pipe segments, and selected PHT system auxiliary rooms.

Fuel Channels

The majority of the heat added to the fuel channels was via the heat up of the main moderator system. The residual water in the pressure tubes was boiled off by heat conducted from the moderator through the calandria tubes, annulus gas and pressure tubes. To allow a more efficient transfer of heat from the moderator system to the fuel channels, the annulus gas system was purged of its CO_2 and replaced with helium, which has a considerably higher thermal conductivity, allowing better heat conduction than CO_2. The application of helium increased the heat transfer rate by approximately 50%. The annulus gas system was placed in stagnant mode to prevent heat loss to the gas. During the vacuum drying process, the annulus gas system was maintained at a pressure between 20 kPa (g) to 55 kPa (g). The temperature of the annulus gas system was maintained between 40°C and 60°C.

To introduce heat to the fuel channels, one of the main moderator pumps was placed in service while the main moderator system heat exchangers were isolated from the cooling water systems. This allowed pump heat to slowly increase the bulk moderator system temperature, which would in turn increase the temperature of the fuel channels. Moderator temperature was controlled between 40°C and 60°C by simply starting and stopping of the moderator pump. The maximum rate of heat-up was less than 0.3°C/min. The moderator pump circulated the heated water through the tube side of the moderator heat exchangers to the calandria where it boiled the residual D_2O in the sagged pressure tubes.

In addition, one of the end shield cooling system pumps was placed in service to heat the shield tank and end shield cooling system. This aided the vacuum drying by providing latent heat to boil the residual water in the portion of the end fittings inside the end shields. It also reduced heat loss from the moderator system and minimized the temperature difference between the end shields and the moderator as mandated by operating procedures which require that the inlet temperature to the end shields be between 46°C and 74°C corresponding to moderator temperatures between 33°C and 70°C.

Feeder Cabinets

External heat sources were used to heat the end fittings and boil the residual D_2O. The feeder cabinets were sealed to prevent air leakage as much as practical, and the internal temperature of the feeder cabinets was increased by using custom designed electric heaters and fans to circulate the air within the cabinets. The heaters and fans were located inside containment and were connected to the feeder cabinets by ducting. Ducting was also installed inside the feeder cabinets to distribute the air beneath the lowest row of end fittings. Thermocouples placed on representative end fittings, allowed for ongoing monitoring of temperatures within the feeder cabinet. The feeder cabinet heaters were set to a maximum outlet temperature of 80°C and the maximum rate of heat up was 2.8ºC/minute. The vault ambient temperature increased to 60°C to 65°C due to the heating of the feeder cabinets and the fuel channels. The maximum vault heat up rate was 10°C/hour.

Pre-heaters

Due to the orientation of the tube bundles, the preheaters at Bruce A were drained only to the level of the tube sheet. The individual 'U' tubes act as traps and remain full of heavy water. Heat was added to the pre-heaters via the shutdown cooling circuit. A temporary heating skid was connected to the shutdown cooling system. The heating skid was located at Bruce A Unit 1, on Elevation 639', between Column D10 to F11. The skid footprint and overall height was restricted to less than 10 feet x 10 feet x 10 feet.

The shutdown cooling system was isolated from the bulk of its system around each of the four pre-heaters. Water to re-fill the shutdown cooling system was provided from the demineralized water system. Additional makeup water was also provided from the demineralized water system. The demineralized water within the shutdown cooling system piping was recirculated through the electric heater incorporated as part of the temporary heating skid. The heater temperature was set at 80°C. The temporary heating skid recirculated heated water through the shell side of the four pre-heaters. Therefore, the recirculating heated water through the shell side of the preheaters, while subjecting the PHT system to vacuum conditions, facilitated the boiling and collection of the remaining D_2O held-up in the tube side of the pre-heaters.

Heating Pads - Valve Bodies and Pipe Segments

Selected valve bodies and pipe segments throughout the PHT and Feed and Bleed systems were wrapped using stress relieving heating pads, similar to those used for post-weld heat treatment. Based on prior operating experience, these locations were suspected of containing held-up D_2O including the Emergency Coolant Injection (ECI) isolation valves. The heating pads were equipped with temperature control devices and utilized existing power outlets. The temperature of the heating pads was controlled remotely between 45°C and 55°C.

Auxiliary Rooms

Selected PHT auxiliary rooms containing instrument lines and small bore piping with trapped D_2O were heated by electric space heaters. The temperature of the rooms was increased as much as practical to promote vaporization of D_2O within these pipes. The temperature of the auxiliary room heaters was controlled locally at 45°C due to hot work limits.

Power Supply and Instrumentation & Control Design

The power needed to supply various heaters, pumps and fans was provided from Class IV power systems, using both 120 V and 600 V supplies. Comprehensive designs for instrumentation and control systems were incorporated to prevent over-heating of the systems.

Heat Up Sequence

The activation of heat sources was conducted slowly. Based on prior operating experience, there was no urgency to activate the heat sources in a rapid manner. Ideally the following sequence should be used:

1. Isolate and establish a vacuum drying envelope.
2. Vacuum was applied to the PHT system and D_2O collection commenced.
3. The moderator was heated slowly to 60°C - 65°C. The end shield cooling system was heated up in parallel.
4. The feeder cabinets were heated using the feeder cabinet heating fans and ducting.
5. The heating skid (connected to the shutdown cooling system) was activated to heat up the preheaters.
6. The auxiliary heaters and heating pads were activated to heat up the various feed and bleed system components, auxiliary rooms, valve bodies, and pipes.

4.4 Bruce A Unit 1 PHT Vacuum Drying Process System

The temporary vacuum drying process system was installed within the Reactor Auxiliary Bay, with components mounted on two floor elevations, 591' and 579'. The vacuum drying pumps and associated equipment were located in Unit 1 on EL 591' near the maintenance cooling system (MCS) heat exchanger room. The D_2O collection equipment was located directly below the vacuum drying equipment on EL 579'. This arrangement allowed for gravity draining of condensate from the MCS heat exchanger and other

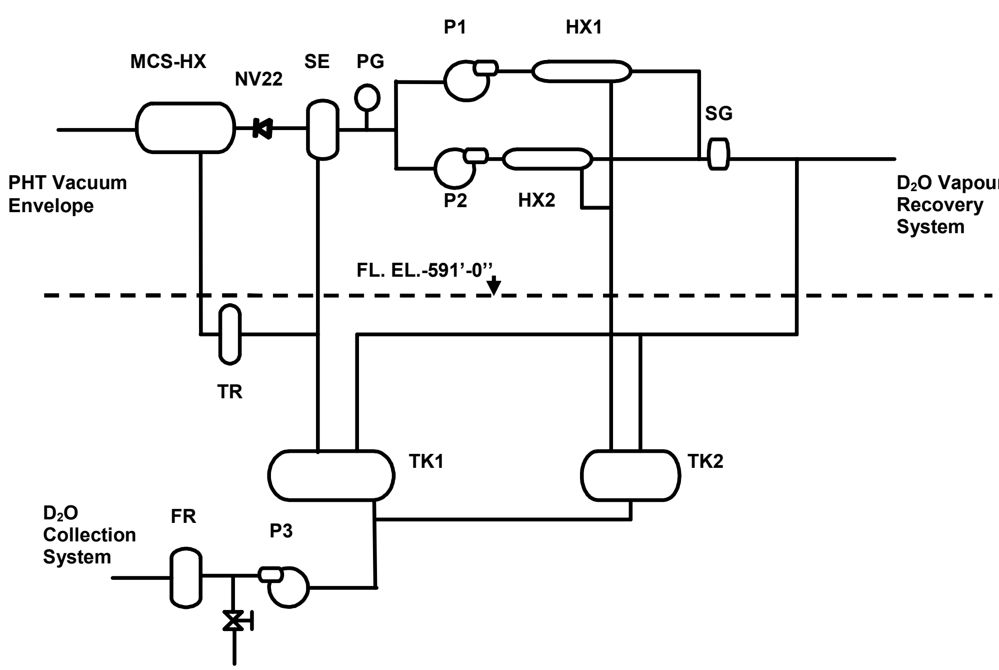

Figure 1 Vacuum Drying Process System

vacuum drying equipment. The system schematic is shown on Figure 1.

The temporary vacuum drying process system was connected to the PHT system through the maintenance cooling system. This allowed the vacuum pumps to be installed outside containment and connected to the heat transport system via large diameter pipes. To reduce the spread of contamination, a rubber area was established and a plastic tent was installed around the vacuum pumps and associated equipment. The tent was ventilated to the containment exhaust stack.

The suction of the vacuum pumps was connected to a separator (SEO) with a vacuum gauge. The separator was connected to the MCS pump discharge check valve NV22 by a six inch vacuum hose. The separator was installed to knock out any D_2O condensed in the vacuum hose prior to passing through the vacuum pumps. Condensate drained from the bottom of the separator into the D_2O condensate collection tank TK1. The top flange of the check valve NV22 was replaced with adaptor flange with the connections to accommodate the six inch vacuum hose.

Two BUSCH COBRA AC800 (rated capacity 495 SCFM each) vacuum pumps (P1, P2) were installed to draw the system to vacuum conditions. The BUSCH COBRA vacuum pump is a single stage, dry-running, water cooled, screw vacuum pump driven by a direct coupled motor. The single-stage design eliminates the problems of interstage condensation, liquid removal, and solid formation. The pump can operate at any pressure from atmosphere down to ultimate pressure. This screw type pump can handle moisture and a small amount of liquid. The vacuum pumps were controlled by individual ON/OFF buttons on a local power supply panel.

Evacuating the PHT system through the MCS allowed the MCS heat exchanger (MCS-HX) to be employed as a condenser. As the shell side flow of the MCS heat exchanger was low pressure service water, a convenient heat sink was available. The MCS heat exchanger was drained to the D_2O condensate collection tank TK1. A condensate pump (P3) was installed to pump the D_2O condensate into the station D_2O Collection System.

The majority of the condensate was removed by the MCS heat exchanger. However, some vapour would pass through to the vacuum pumps and condense in the pump exhaust coolers (HX1, HX2). The vacuum pump exhaust coolers were used to cool and condense some of the remaining vapour flowing from the outlet of the vacuum pumps. Cooling water from the Low Pressure Service Water System cooled the vacuum pumps and the vapour flow. The D_2O condensate collected in the coolers drained by gravity into the D_2O condensate collection tank TK2. The two D_2O consensate collection tanks (TK1, TK2) were automatically pumped out by a condensate pump when the D_2O consensate reached the high level setpoint. When the D_2O condensate reached the low level setpoint, the pump was set to stop automatically. The two tank cycle counters corresponded to TK1 and TK2 respectively and record the number of times that the high level switch was activated for each tank. This allowed the determination of the quantity of D_2O collected during the vacuum drying operation. The collection rates were also monitored by pump-outs from the station D_2O Collection System.

A sampling/drain valve was fitted on the downstream of the condensate pump to sample the D_2O condensate druing the vacuum drying operation. The valve also allowed for draining of the discharge line of the condeansate pump.

Non-condensed vapour and gases were discharged to the Confinement D_2O Vapour Recovery System via a three inch hose. A sight glass (SG) was fitted on the downstream of the exhaust coolers to provide a visible means of assessing the condition of the discharge from the vacuum dry equipment.

A particle trap (TR) was installed on the upstream of the D_2O condensate collection tank TK1 to trap radioactive particulate that might come out of the MCS heat exchanger. The trap was fitted with a drain valve and a vent valve so that it could be flushed if necessary. A D_2O filter (FR) was installed on the downstream of the consensate pump to filter out the radioactive particulate that might be carried out of the PHT system by the flowing water. The differential pressure across the filter was monitored and the filter would be changed as required. The trap and filter also needed to be monitored for radiation and appropriate radiation protection procedures were implemented.

Operating Performance

The vacuum drying process was operated with the use of the following existing systems: Main Moderator, Moderator Cover Gas, Moderator Purification, End Shield Cooling, Annulus Gas, and Heat Transport D_2O Collection; and in conjunction with the operation of the newly designed and temporary installed systems: Vacuum Drying Process System, Pre-heater Heating Skid, Feeder Cabinet Heating System, Heating Pads, and Auxiliary Room Heaters.

The vacuum drying process system was operated automatically with supervision from the Bruce A Main Control Room. The vacuum conditions were maintained with a pressure controller and a sensor installed on one PHT header. If the pressure was above the setpoint, the selected vacuum pump would start to reduce the pressure to the setpoint. If the pressure was below the setpoint, the pump would stop and remain off until the pressure was above the setpoint. Bacause of the air leakage ingress, the setpoint of pressure was set up at the point which kept the pump(s) running without stopping the vacuum drying operation.

The Bruce A Unit 1 PHT vacuum drying process commenced on July 3, 2007. The vacuum drying operation for Unit 1 was completed on August 22, 2007 in which the PHT and its auxilliaries were declared functionally dry. Based on the estimation of water trapped in the system, the process was planned to operate 30 -35 days. However, the vacuum drying process had been extended due to the vacuum drying envelope leakage and equipment problems.

At the beginning of the operation, the isolated system could not maintain the expected vacuum pressure. An extensive investigation was executed to search for leakage sources. The potential leak locations had been checked systemically. It was determined that the source of the large air ingress was from the boilers. Although customized bungs were installed inside the boilers to prevent leakage from the steam generator tube bundles suspected of having cracks, significant leaks were still present. Technical assessments concluded that if the boiler manways were closed and sealed, this would mitigate the air ingress. As the existing boiler manway doors were defective and in some cases removed, a temporary set of boiler manway covers was designed and installed. Subsequently, the vacuum system reached its expected vacuum conditions. The lessons learned are that the steam generator tube bundles do not leak significantly as expected, however the boiler manyway covers must be closed to maintain an effective vacuum envelope.

After the mitigation of the system leaks, a relatively tight vacuum drying envelope was achieved and the vacuum pressure reached to approximately -96 kPa (g). The vacuum drying process operation started in July 2007 in which heavy water was collected since the beginning of the process. The heating sequence deviated from the original plan due to equipment unavailability. The heavy water collection rate is shown on Figure 2.

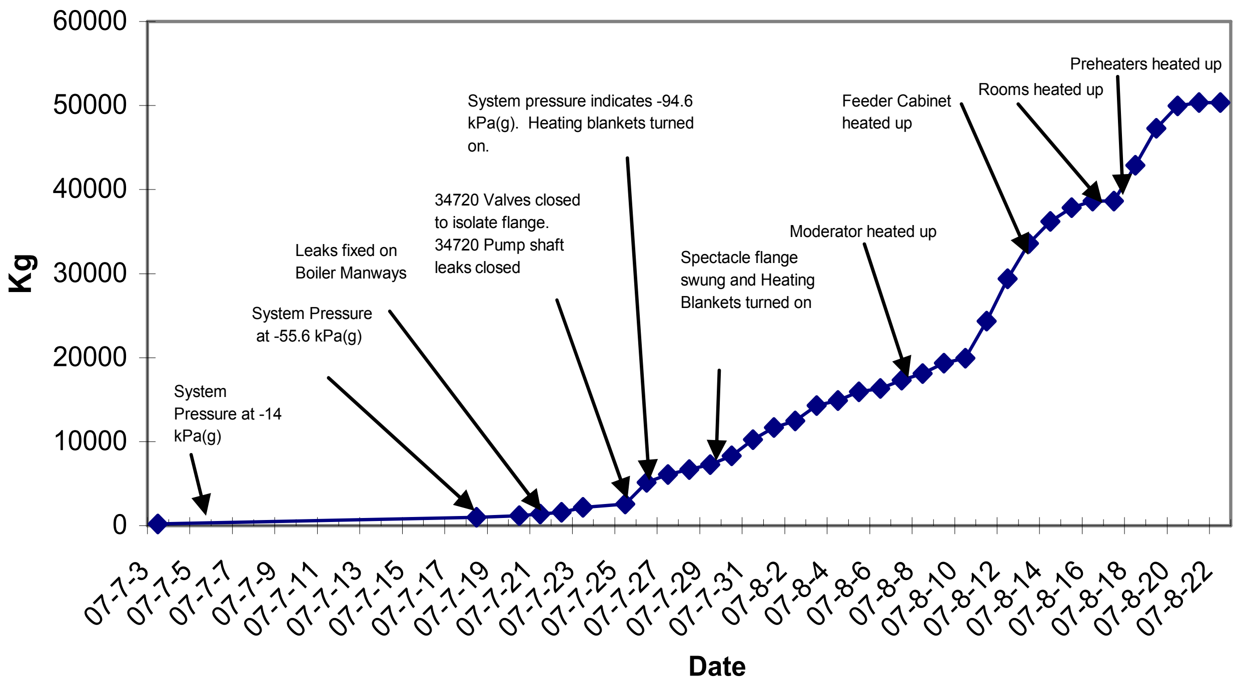

Figure 2 D_2O Collection Rate

Figure 2 shows the collection rate associated with each significant operating event throughout the vacuum drying process. The highest vacuum achieved was -97.6 kPa (g) during the last week of operation. The total collected heavy water was about 50 Mg which was stored in D_2O drums. Periodic samples of D_2O were collected and analyzed for isotopics. The vacuum drying process was declared complete when water was no longer being collected from the maintenance cooling heat exchanger, or very low isotopic water (~0.02%) was being collected and measured tritium concentration was low and stable over a 24 hour period. After the vacuum drying operation, a lower end fitting was opened and it was confirmed that the pressure tube was dry.

5 CONCLUSIONS AND RECOMMENDATIONS

The following conclusions were observed:

1. Boiler tube bundle leakage is typically not a source which can break the vacuum drying envelope. The boiler tube leaks could be overcome by a strong vacuum pump. The bungs are not necessary to be installed to isolate the boilers unless the tube leak is identified as significant causing the vacuum envelope to break. To optimize the vacuum drying envelope, the boiler manway covers should be closed and a tight seal maintained.

2. Consideration should be taken in the selection of equipment, instrumentation and controls used by a vacuum drying process system. Some components will have functional changes under vacuum to cause problems with operation.

3. By utilizing a properly isolated drying envelope and applying sufficient heating sources, the vacuum drying process system is the ideal method to dry the primary heat transport system of a CANDU nuclear power plant.