36th Annual Conference of the Canadian Nuclear Society and 40th Annual CNS/CNA Student Conference
Toronto Marriott Downtown Eaton Centre Hotel, Toronto, ON, Canada, June 19-22, 2016

VACUUM DRYING STRATEGIES FOR CANDU POWER PLANTS

S. Fernandes[1] and M. Singh[1]
[1] Amec Foster Wheeler, Toronto, Ontario, Canada
steve.fernandes@amecfw.com and mayank.singh@amecfw.com

Abstract

Nuclear power plants often require prolonged maintenance or refurbishment outages in order to replace or refurbish various critical components. In order to isolate key piping systems in a dry state, various draining and drying techniques can be applied (e.g. dry air purge, drying by heating). Vacuum drying is a technique that reduces the temperature at which evaporation can occur by lowering the air pressure within the piping. The drying of either light or heavy water results in a significant reduction of radioactive dose, emissions and associated hazards during maintenance. However, specialized equipment (vacuum pumps, heat exchangers, heaters, etc.) are required in order to successfully implement vacuum drying in the primary heat transport or moderator systems in a CANDU plant. This paper explores vacuum drying strategies and equipment considerations across previous nuclear refurbishment outages and outlines some recommendations for future outages (primarily the Ontario Power Generation's Darlington Unit 2 Refurbishment).

1. Introduction

Nuclear power plants often require prolonged maintenance or refurbishment outages in order to replace or refurbish various critical components. In order to isolate key piping systems in a dry state, various draining and drying techniques can be applied (e.g. dry air purge, drying by heating). Vacuum drying is a technique that reduces the boiling temperature at which drying can occur by lowering the pressure in the piping. The drying of either light or heavy water results in reduction of radioactive dose and associated hazards for maintenance (tritium exposure). Specialized equipment (vacuum pumps, heat exchangers, area heaters, etc.) is required in order to successfully implement vacuum drying in the Primary Heat Transport or Moderator systems in a CANDU plant. This paper explores vacuum drying strategies and equipment considerations across previous nuclear refurbishment outages and outlines some recommendations for future outages (primarily the Ontario Power Generation's Darlington Unit 2 refurbishment).

2. Background

2.1 Vacuum Drying

Vacuum drying is required when the dried state achieved after draining a piping system is not wholly adequate for equipment maintenance or refurbishment. Vacuum drying is a process where liquid from the drained system is removed under reduced air pressure which promotes boiling at a lower temperature. In other words, the boiling point of light water (H_2O has a boiling point of 100°C at atmospheric pressure) or heavy water (D_2O has a boiling point of 101.42°C at atmospheric pressure) is reduced as the atmospheric pressure is reduced (e.g. D_2O's boiling point reduces to 26.5°C at approximately -97kPa(g)). Evaporation can be further accelerated with the addition of heat. Vacuum drying is particularly advantageous in the nuclear industry because the process fluid (light or heavy water) may be tritiated and evacuation of this fluid from piping would reduce radiological exposure for workers.

2.2 Description of PHT/Mod systems (main and auxiliaries)

The vacuum drying system (VDS) works by reducing the pressure inside the primary heat transport (PHTS) system and its auxiliaries to below the saturation pressure of the water inside the system to promote boiling/evaporation, thereby generating D_2O vapour. This vapour is exhausted in part through heat exchangers, which cool and condense the vapour due to the cooling water temperature (i.e. service water temperature at summer time) and mainly condenses at plate heat exchangers cooled by chilled water. Any remaining vapour is further condensed and collected using additional coolers and moisture separators on the vacuum drying system. The recovered condensed D_2O is delivered back to the plant via a Condensate transfer skid which is part of the overall PHTS VDS.

2.3 Description of main components of skids

The VDS can be divided into eight independent functions:

1. Vacuum/Condensate skids– draws vacuum, condenses and collects D_2O.
2. Plate type heat exchanger (PHX) is installed on the process side of the PHTS vacuum drying system. The function of this skid is to further condense any remaining vapour being released from the station's first-stage heat exchangers (i.e. existing station Shutdown Cooling System Heat Exchanger).
3. Air Injection – Injects air into the PHTS and its auxiliaries to purge the system of D_2O moisture that may be held up in crevices or other tight spots.
4. Feeder Cabinet Heating – Adds heat to the feeder cabinets to evaporate the D_2O within the feeders and the system low points.
5. A chilled water system that is required to meet following requirements:
    a. The plate type heat exchanger (PHX) skid requires chilled water connection to its secondary side to cool and condense D_2O vapour.
    b. Secondary condenser downstream of vacuum pumps requires chilled water to cool and condense hot vapour coming out of the vacuum pumps.
    c. Vacuum pumps require chilled water to cool the pump casing.
6. Localized heaters or heat blankets – Promotes evaporation in low point areas or inside large components such as heat exchanges that accumulate some D_2O.
7. End Shield Cooling System heated to highest acceptable temperature and Moderator system circulating at the D_2O vapor pressure temperature – Promotes the evaporation of the D_2O accumulated in sagged areas of the pressure tubes
8. Helium Injection – Injects Helium into the Annulus Gas System to promote greater heat transfer between the D_2O circulating in the moderator system outside the Calandia Tubes and the D_2O water that is being evaporated due to vacuum inside the Pressure Tubes. The ratio of specific heat (k-

value) for Helium is approximately 30% higher than the k-value of CO_2 that is normally in the Annulus Gas system [6].

3. Equipment considerations

3.1 Collection rates across past campaigns

Vacuum drying of the Primary Heat Transport system has taken place at several CANDU power plants including the Wolsong plant in South Korea and the Pickering, Bruce, Point Lepreau, and Gentilly stations in Canada. Vacuum drying is currently being planned for the OPG Darlington Refurbishment Project. Vacuum drying may sometimes be performed on critical path during a refurbishment campaign as the PHT system being drained and dried of D2O is required prior to feeder and fuel channel removal. As such, the time to drain the PHT system and complete vacuum drying is an important metric that is tracked across the different vacuum drying campaigns.

The table below provides a summary of the vacuum drying time-lines across multiple campaigns and the associated D_2O collected.

Table 1: Vacuum Drying comparisons over previous refurbishment outages [1] [2] [3] [4] [5]

Unit	Vac Dry Duration (estimate)	D_2O Water Collection	Vacuum Pressure
Bruce A U1	50 days	50 Mg	run at approx -96 kPa (g)
Pickering U1	9 days	19 Mg @ 17% isotopic	-80 to -95 kPa (g)
Pickering U2	6 days	13.3 Mg @ 8% isotopic	-80 to -95 kPa (g)
Wolsong U1	9 days	N/A	N/A

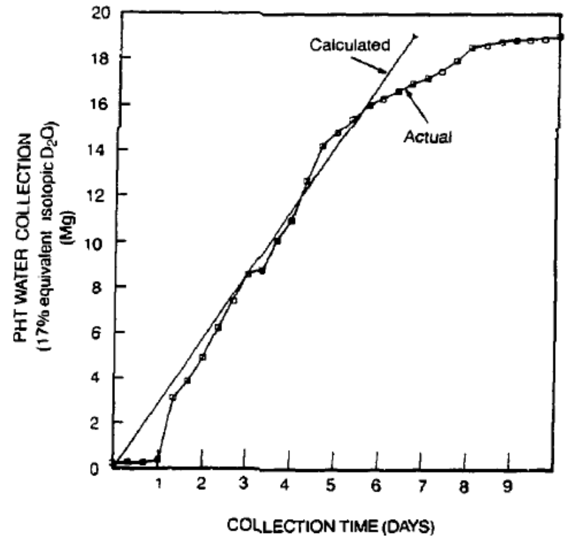

Figure 1: Collection during Vacuum Drying of Unit 1 Pickering A [1]

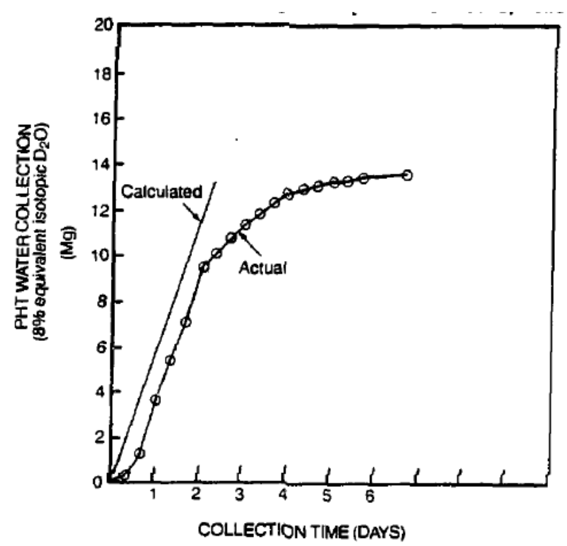

Figure 2: Collection during Vacuum Drying of Unit 2 Pickering A [1]

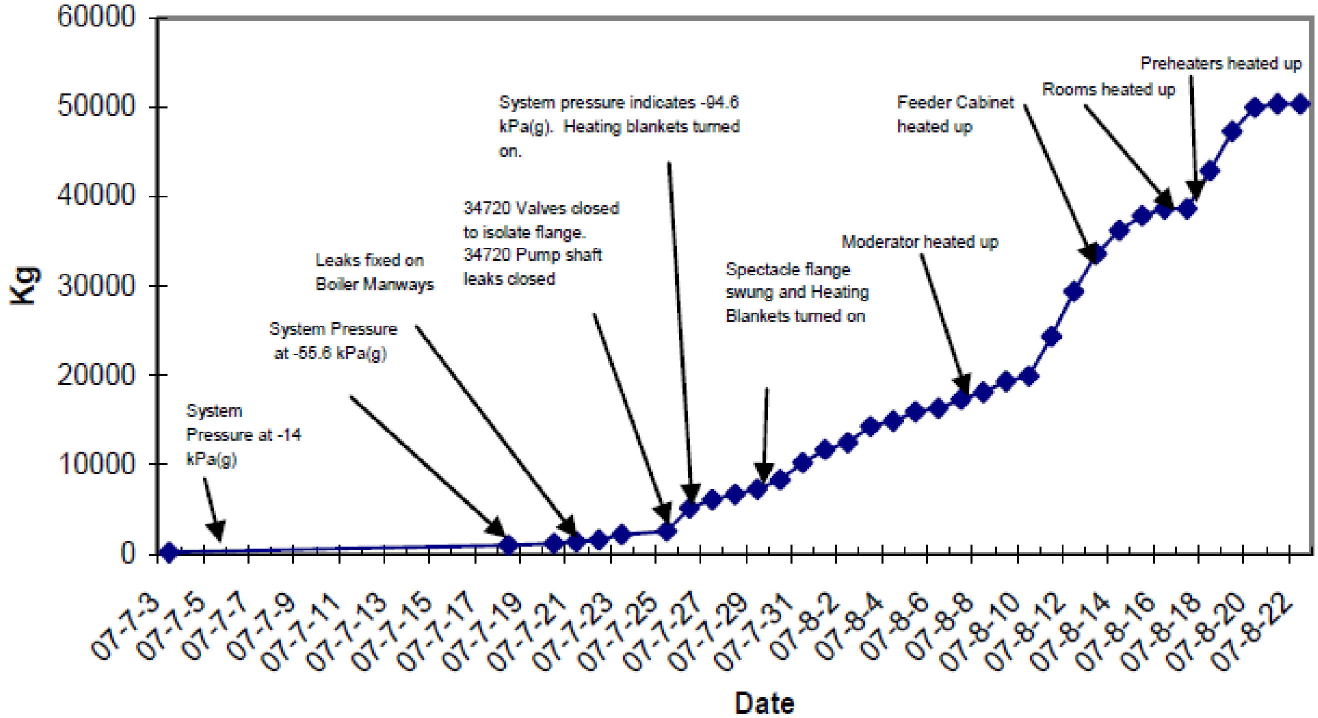

Figure 3: Collection during Vacuum Drying of Unit 1 Bruce A [4]

The Bruce A U1 vacuum drying of the PHTS took longer than expected due to problems with the isolation boundaries [4]. Vacuum drying depends on a complete isolation boundary that involves closing of valves, removal of spool pieces and installation of blind flanges (where applicable) to guarantee a full seal to support vacuum drying. Bruce U1 also had gradual heat addition via the main Moderator System, Feeder Cabinet Heating, warming of the Pre-Heaters, and the addition of heating pads (heat blankets) on specific valve bodies and pipe segments. Heating to promote vaporization of D_2O is a necessary part of the vacuum drying process. Heating pads were used on piping low-points where it was expected that water would be held up.

For the Bruce A U1 campaign, it can be inferred, based on Figure 3, that collection of D_2O spikes after the addition of new heating sources (moderator, feeder cabinet, instrumentation rooms, pre-heaters). A consideration for future campaigns should include all sources of heat initialized from campaign kickoff rather than over time.

The Pickering Units 1 and 2 PHT vacuum drying used a similar approach with one vacuum pump running constantly and heat addition through the Moderator System and through Feeder Cabinet heating [1]. While a smaller amount of D_2O was collected at Pickering 1, collection times were half of what they were at Bruce A Unit 1, as shown in Table 1.

Additionally, Figures 1 and 2 indicate a drop in collection against the calculated values. This is because at that point in the campaign, the collection rate reduces as the system is only drying the low points and therefore evaporating from a reduced surface area. Strategies to improve collection rates include adding heating blankets at these low points and air injection to promote evaporation.

3.2 Vacuum Pumps

Vacuum pump design involves ensuring that the system can be subjected to near-absolute vacuum pressures while handling small droplets of the process fluid. The Bruce A vacuum drying campaign used a single-stage, dry-running, water-cooled screw-type vacuum pumps with direct coupled motors [4]. These pumps were able to handle small water droplets passing through. The earlier Pickering Unit 1 design faced some seal water circulation problems, causing one of the vacuum pumps to be shut down for the majority of the drying operation [1]. Vacuum pump redundancy needs to be a major consideration during vacuum drying. In both the Bruce and Pickering campaigns, redundancy within design ensured that the vacuum drying process did not stop due to pump failures or maintenance.

Parameters for vacuum pump sizing during design are typically based on the approximate volume of water required to dry, vacuum pressure (based on condenser performance), and the approximate required flow rate (standard cubic feet per minute) based on potential leak paths in the isolated system. Vacuum pumps are typically coupled with a water separator at the suction end to eliminate water droplets from entering the pump body and heat exchangers and localized tanks for condensate collection.

Vacuum pump effectiveness depends solely on a leak-tight isolation boundary. A higher number of leak paths for air to flow into the isolated system will necessitate larger vacuum pumps. At Pickering, over 100 valves were closed to establish an effective isolation boundary [1]. However, all vacuum drying processes must be designed to handle air ingress through passing valves and flanged connections. Therefore, the overall vacuum pressure applied onto the system can fluctuate throughout the process. The Bruce A campaign required troubleshooting in-situ to determine where major leaks were coming from, which greatly extended the overall drying time [4]. The Darlington Unit 2 design incorporates the lessons learned from past campaigns and engineering involves secondary isolation points and a low point assessment which identifies spots where water may be held up and therefore need point-source heating (heat blankets), a vacuum boundary assessment involving a phased approach to vacuum drying, and a vacuum assessment to ensure piping and components are capable of handling the pressures exerted by the pumps.

3.3 Heat Exchangers

Vacuum drying involves the direct use of Heat Exchangers and collection tanks to recover D_2O that has been condensed through the process. Heat exchanger selection is dependent on the amount of space available and the associated throughput. Efficiencies can be gained by using heat exchangers that depend on cooling water from the station, if applicable. Additionally, the vacuum drying process can be further supported by the inclusion of existing station heat exchangers as the first stage to condense water. In CANDU stations this is the case where a system such as Shutdown Cooling is tied directly into the D_2OCollection System.

Available space is one of the primary considerations when designing a Heat Exchanger for vacuum drying. An air-cooled or refrigerant-cooled heat exchanger can be used instead of using station systems to provide cooling water, as some vacuum drying campaigns do not have the opportunity to use station cooling water systems. Cooling water, unless coming from a chilled water system that has a specific design temperature, is also impacted by the summer and winter temperature fluctuations affecting the body of water being used as the source. This needs to be taken into consideration when performing heat exchanger design; while vacuum drying may be planned for winter months when the temperature is relatively low, project delays may shift the existing schedule. Alternatively, process cooling water needs to have a specified minimum set point for winter months as D_2O freezes at 3.8°C.

Using a refrigerant-based heat exchanger is also possible. However, the designers need to consider the possibility of a refrigerant leak or a large-scale failure. Refrigerant that leaks into the atmosphere, especially in a closed area, is an asphyxiation hazard and is not able to be processed/broken down. Therefore, a large leak or failure can effectively terminate vacuum drying operations until the refrigerant is exhausted from the room or the containment structure. In some CANDU plants, the vault's atmosphere D_2O management system (referred to as VVRS - Vault Vapour Recovery System) may be shared with other adjoining systems via the fueling machine duct. This means that a large-scale refrigerant leak has the possibility of being recirculated into other unit vaults before being exhausted into the atmosphere. The risk increases in newer CANDU 9 units where the reactor building is smaller than that of a CANDU 6 unit. Therefore, the use of a refrigerant-based heat exchanger is less advantageous when the failure modes and corresponding recovery actions are considered.

3.4 Piping, Hoses, Heat Blankets and Other Sources of Heat

In Pickering A Unit 1, the PHTS was drained of D_2O and H_2O with the shield plugs in place. This resulted in significantly more water remaining in the system than originally envisaged (19 Mg vs. 7 Mg) [1]. As such it is recommended to remove any additional low points and volume traps during drain operations to further limit the amount of vacuum drying that needs to occur.

Areas suspected of containing held-up D_2O in a system are called "low points". Low points which cannot be heated by station systems are of particular concern during vacuum drying as the normal drying process is not as effective in drawing out the D_2O. As such, heating blankets can be used to raise the temperature of the process fluid and aid evaporation. The use of heat blankets or heating pads for point-source heating is a common element across different retube campaigns. The Bruce A Unit 1 vacuum drying campaign used heating pads on selected valve bodies and piping segments throughout some of the PHT Auxiliary systems (Feed and Bleed circuit, Emergency Coolant Injection System) in order to target held-up D_2O. The heating blankets were remotely controlled and the temperature was kept between 45°C to 55°C.

Point source heating is effective because it targets areas with water held up. During the Pickering PHT vacuum drying campaign, the moderator system reached a temperature of 55°C, with a vacuum pressure of approximately -95 kPa (g). Since the boiling temperature of D_2O at -95 kPa (g) is approximately 38°C, it was concluded in the Pickering campaign that water was boiling in the fuel channels [1]. With similar vacuum pressures across other campaigns, point-source heating using heating blankets provides the localized increase in temperature to aid the boiling process. The Bruce A Unit 1 vacuum drying campaign also used ambient air space heating in selected PHT Auxiliary System rooms containing small bore piping and instrument lines. In this case, the temperature of the auxiliary room heaters was controlled locally to 45°C due to hot work limitations.

3.5 Other Options - Emissions Considerations

The main purpose of a PHT vacuum drying campaign is to remove as much D_2O from the system as possible, in order to protect workers and avoid D_2O spills inside the unit Vaults during Calandria re-tubing activities. However, all vacuum drying campaigns are a source of emissions. While the majority of the D_2O left in the PHT system after draining is vaporized and condensed, a small portion consisting of water vapour-laden air is emitted into the atmosphere. Emissions must be carefully tabulated and planned for in advance of the vacuum drying campaigns in order to ensure that the station limits are not breached. Public opinion of station refurbishment is dependent not only on a successful project but also the control of emissions throughout the campaign.

The vacuum drying campaign captures large volumes of water, as seen in the data in Table 1. Plant D_2O collection systems must be capable of accepting a large volume of water in a relatively short duration (< 30 days, as seen in the data in Table 1) in order to avoid costly handling and storage of D_2O drums. In the Bruce A Unit 1 vacuum drying campaign, approximately 50,000 L of D_2O was captured and stored in drums (approximately 250 drums containing 200L each), which required periodic sampling, interpreted to be very labor intensive. [4]

4. Recommendations

4.1 Drying during maintenance outage

The following considerations should be reviewed when designing a vacuum drying strategy for a maintenance or refurbishment campaign:

- Ensure heat addition is provided from the start of the vacuum drying campaign.
- Consider whether vacuum drying is necessary on smaller auxiliary Primary Heat Transport systems as air drying might be more cost effective.
- Establish a firm vacuum boundary with bungs and other modifications (blind flanges, spool piece removal, pipe caps, etc.) to ensure vacuum pressure builds quickly and effectively. Troubleshooting is costly and has the potential to impact outage critical path.
- Consider re-purposing vacuum pump assemblies for other uses (e.g. Moderator Auxiliary System drying, as DNGS is planning)
- Ensure station D_2O collection systems are capable of handling the volumes input in a short duration.
- Focus on tritium emissions from vacuum drying as station targets need to be adhered to.
- Avoid designing heat exchangers that use a refrigerant if being placed inside the vault or confinement rooms.
- Establish firm drying criteria and a contingency plan up-front.
- Perform assessments to define what the total volume of water held up will be to avoid untimely surprises and monitor water accumulation at low points against estimates calculated.
- Monitor pressure and temperature at key locations to ensure the process is effective throughout the system

4.2 Other Drying Considerations

Emissions are important considerations for the station owner. Drying campaigns often may require the vapour exhaust to vent to the vault vapour recovery systems. A vault vapour recovery system in the plant would then provide a fraction of this vapour to the active ventilation system which ultimately is distributed through the emissions stack.

A critical path assessment can also be used to save valuable time during a refurbishment outage. In some CANDU stations, draining of fuel channels is a cumbersome process and may not be necessarily prior to vacuum drying. A "bulk drying" strategy can be implemented which involves drainage of the PHT system down to the feeder headers, followed directly by vacuum drying rather than channel drainage. A bulk drying strategy would rely heavily on heat addition to improve D_2O collection rates during the initial phase of drying when D_2O is evaporated from the headers, feeders and fuel channels. This type of strategy can reduce or eliminate the amount of radioactive crud/particulate matter that would have otherwise have been captured within particulate filtration of the channel drain system. This type of strategy to eliminate channel draining has the potential to reduce waste collected in the particulate filters.

5. Acknowledgment

We would like to thank Amec Foster Wheeler, SNC Lavalin, CANDU Energy, and Ontario Power Generation for their help. Specifically, we would like to personally thank Raymond Baker, Benjamin Xu, Rosemary Hernandez, Andrew Cerilli, Eduardo Ghelman, Brian Murdoch, Greg Morandin, Marc Paiment and Glenn Rossitter for providing their input and support.

6. References

[1] P.J, Ellis, T. Lau, and D.G. Meranda "Vacuum drying of Pickering A Units 1 and 2 Primary Heat Transport Systems," *Canadian Nuclear Society 1985 6th Annual Conference*, **54**, 102 (1985)

[2] Bruce A Unit 1 return to Service date - Oct 22, 2012. <<http://www.transcanada.com/6131.html>>

[3] Darlington U2 Outage Duration - Oct 2016 to 2019.
<<http://www.power-technology.com/projects/darlington-nuclear-generating-station-refurbishment-ontario/ >>

[4] B. Xu; Y.C. Hoang, "The primary heat transport system vacuum drying of a CANDU power plant." *International conference on CANDU maintenance*; Toronto, Ontario (Canada); (2008)

[5] Canadian Nuclear History – Nov 25, 2009.
<<https://www.cns-snc.ca/media/history/canadian_nuclear_history.html>>

[6] Ratio of Specific Heat for Gases. Date Retrieved: May 11, 2016.
<<http://www.engineeringtoolbox.com/specific-heat-ratio-d_608.html>>