Pickering Unit 7 Calandria Tube leak operational impacts

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Abstract

In September 2005 Pickering Unit 7 developed a calandria tube leak. As a result the moderator experienced elevated levels of total inorganic carbon (TIC). While in the over-poisoned guaranteed state in April 2009 oxalate complexation of gadolinium necessitated the draining of the moderator, replacement of the calandria and pressure tubes and removal of gadolinium deposits. Significant reactor safety review was required to ensure the reactor could be safely restarted and controlled predictably. This project required the development of many tools and techniques not previously used at Pickering.

1. Introduction

The Pickering Nuclear site houses eight 540 MW CANDU Pressurised Heavy Water Reactors (PHWR). The fuel is housed in horizontal fuel channels and cooled by the Primary Heat Transport (PHT) system. The fuel channels run through a vessel containing heavy water which acts as a moderator to slow down or thermalise the neutrons. The fuel channel assembly is constructed of an inner pressure tube and an outer calandria tube. The gap between the tubes is occupied by the CO_2 of the Annulus Gas System (AGS).

2. Calandria tube leak location

A leak of CO_2 into the Moderator System was originally detected in September, 2005. The leak was detected through falling annulus gas dew point and increasing moderator conductivity. Leak source was verified as CO_2 by total inorganic carbon analysis of the moderator. Within a few weeks it was determined that the source of the CO_2 ingress into the Moderator System was from the AGS, however, it was not known immediately which channel was leaking CO_2 into the moderator or the specific flaw/defect that could be present. Over the course of several months, due to both planned and serendipitous activities, the specific leak location was narrowed to the point were fuel channel A13 was positively identified as the leaker (Figure 1). Final proof was obtained during the outage in 2009 when a “dry ice” plug was formed in the “pigtails” on either side of A13 and the leak location was confirmed by the change in pressure drop rate.

One Technical Operability Evaluation (TOE) and several Operational Decision Meetings (ODM) were completed dealing with the leakage of CO_2 into the Moderator System, however, the prime area of concern was the AGS ability to detect pressure tube leaks or system material integrity. The issue of poison stability was considered but unfortunately testing of gadolinium solution stability testing did not include the impact of radiation on dissolved CO_2.

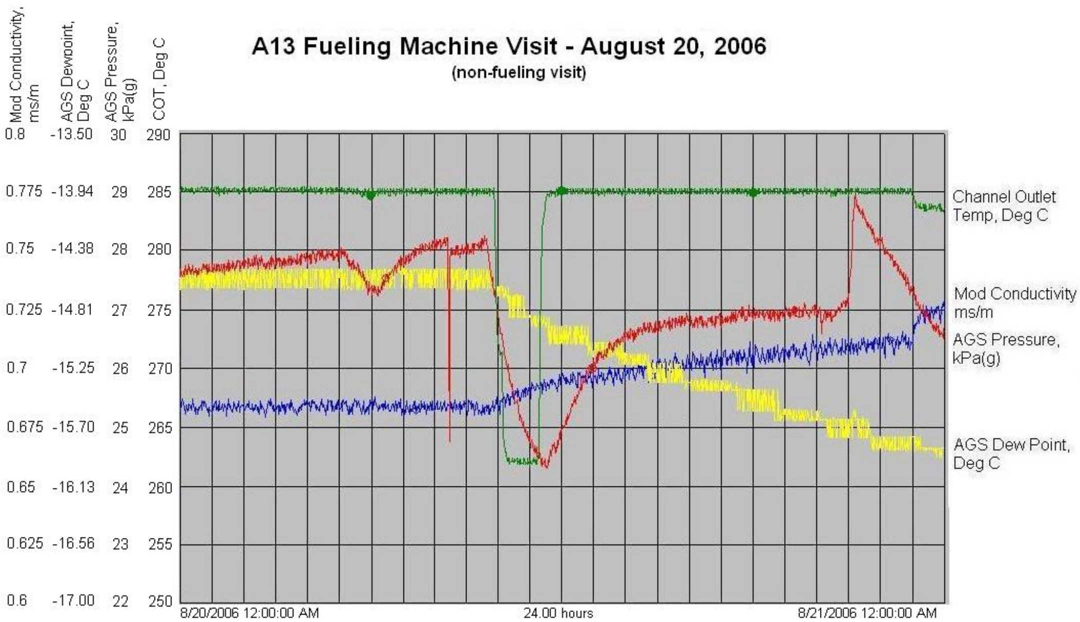


Figure 1 Process changes resulting from a fuelling machine visit to channel A13

3. Moderator chemistry during leak

Prior to April 2008 there had been three outages on unit 7 where gadolinium was used to establish the over-poison guaranteed shutdown state. No evidence of unusual behaviour was seen during these outages. The CO_2 leak rate was tracked and was seen to vary over time (Figure 2). The AGS pressure drop rate was also tracked and showed a similar pattern.

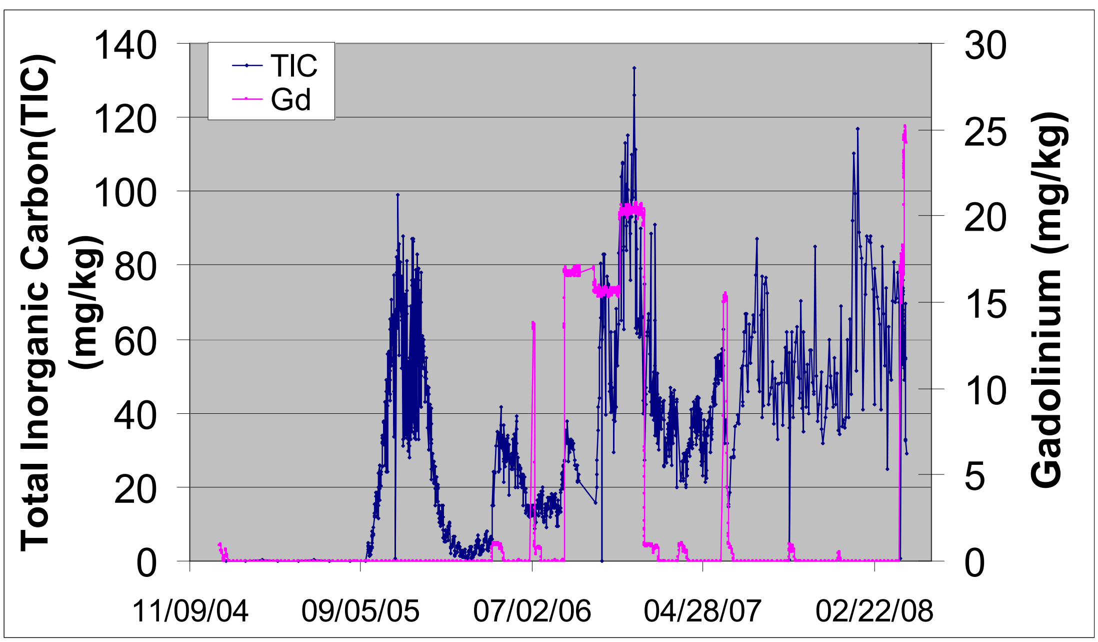


Figure 2 Moderator Gadolinium and Total Inorganic Carbon over life of the leak

4. April 2009 outage reactivity changes

On #1 shift April 06, 2008, Unit 7 was shut down due to a human performance event during the Unit 8 Planned Outage which caused a turbine-generator trip on Unit 7. On #2 shift April 06, 2008, the transition to the Over Poisoned Guaranteed Shutdown State (OPGSS, also known as RSG1) commenced. Delayed due to an apparent flow blockage in the LZCS, between CV2 and zone #14, the RSG was declared in effect on #2 shift April 08, 2008. On April 09, 2008, the Unit 7 moderator gadolinium concentrations began to decrease at a rate of ~2 ppm/day following ~30 hours of stability (Figure 3). The decrease in gadolinium concentration was accompanied by a corresponding increase in sub-critical reactor power. As a result, periodic additions of gadolinium had to be made to maintain the gadolinium concentration above the 14 ppm administrative limit (N.B. the license limit is 12 ppm). Due to the instability in poison concentration while in RSG1, Operations determined that an alternate GSS that did not rely on gadolinium was required. As a result, the drain of the Moderator System commenced #2 shift on April 15, 2008 and the Drained GSS (RSG3) was declared in effect on #2 shift April 20, 2008.

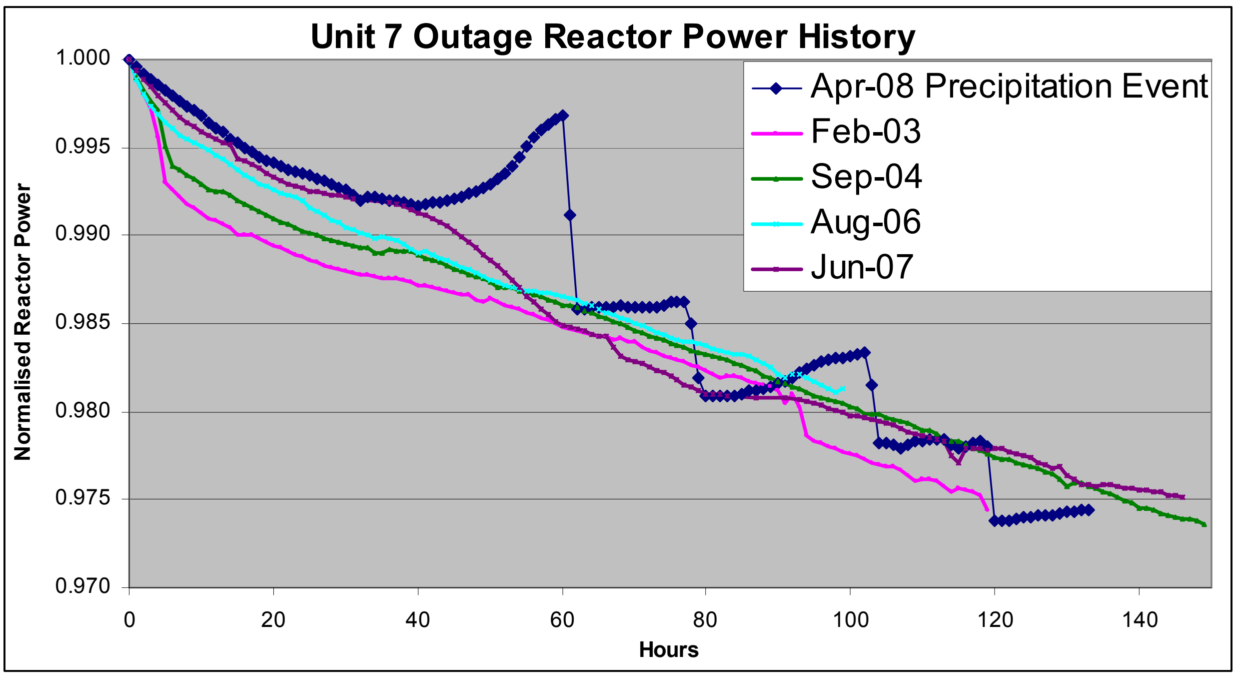


Figure 3 Unit 7 Post Shutdown Reactor Power History

The Root Cause Investigation that was conducted determined that the cause of the decreasing poison concentration was the result of gadolinium precipitation (Figure 4). The gadolinium precipitation was the direct result of the high CO_2 source term (dissolved CO_2) that was present. In the presence of appropriate levels of radiation the CO_2 was converted into oxalate which forms an insoluble precipitate with gadolinium. Prior to the drain of the system, the equivalent of ~11.9 ppm (or 3 kilograms)of Gd went missing from solution. As this gadolinium was not dissolved in the moderator water, it was assumed at the time that it had either deposited on the internal surfaces of the system or had settled in low flow areas. Normally, Unit 7 would be expected to go critical with 0.95 ppm of dissolved gadolinium present in the moderator inventory. The missing gadolinium was well in excess of what would preclude criticality from being achieved.

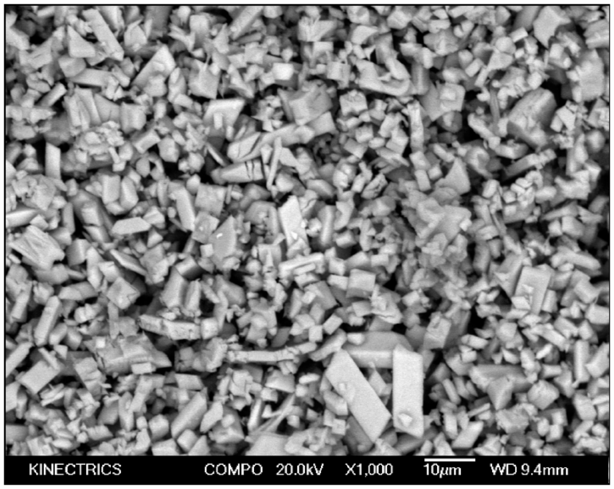


Figure 4 Gadolinium oxalate deposit removed from valve internal

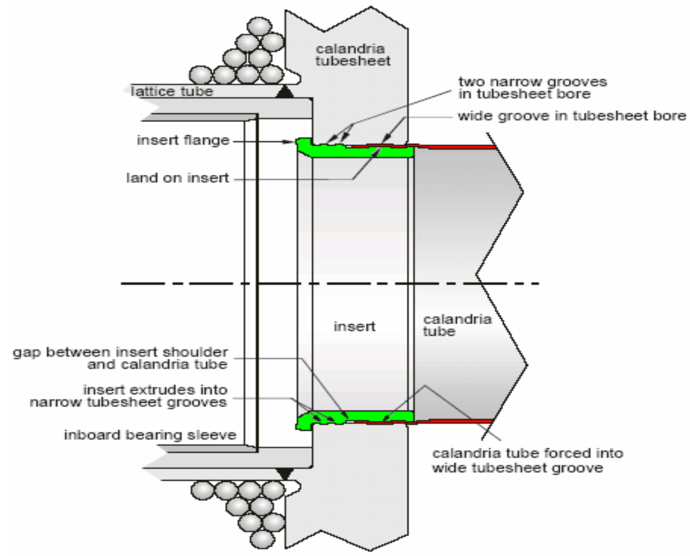
5. Repair strategy

As soon as it was determined that the Gd precipitation was the result of the elevated CO_2 levels into the Moderator System, the decision was made to repair the calandria tube leak. This would involve, as a minimum, the replacement of both the Pressure Tube and Calandria Tube in the leaking fuel channel. As it was not known what the specific flaw/defect was, developing the specific repair strategy was problematic. A multi discipline team was formed to address the various facets of the repair/recovery strategy.

The recovery of the unit was broken into four distinct phases, which included:

- Locating and eliminating the leak of CO_2 into the Moderator System
- Assessing how the Gd was distributed throughout the system (both in and out of core)
- Remediating the moderator system including clean up of the removed D_2O and preparing for the removal of the precipitated Gd oxalate (contingency)
- Developing the safety case for returning the unit to power with Gd oxalate present on internal surfaces, both in and out of core including obtaining CNSC approval for a GSS based on guaranteeing reactivity devices in core (SA's, CA's and AA's) and GSS surrender and HTS warm up.

The repair of the leak would require the removal and replacement of both the pressure and calandria tubes. While pressure tube replacement is not common the station had executed this work previously. Calandria tube replacement had not been completed and required a great deal more development work for equipment and procedures. Additionally the nature of the calandria tube flaw was not known. The flaw could exist at the joints between the tube and tubesheet or in the body of the tube (Figure 5).



Calandria Tube Rolled Joint Arrangement

Figure 5 Cross section of calandria tube rolled joint

Following removal of the pressure tube on reactor testing revealed that the leak was not likely in the rolled joint area of the calandria tube. Inspection of the body of the tube following removal showed the presence of a 7 cm through wall flaw on the bottom of the calandria tube (Figure 6).

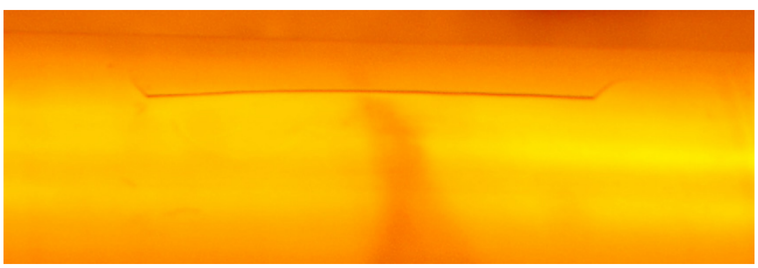


Figure 6 Photograph of flaw in the removed A13 calandria tube

6. Recovery Strategy

It was recognized very early in the recovery effort that a chemical clean of the Moderator System was a very real possibility. It was also determined that any practical chemical clean process would involve the use of water as the chemical carrying medium and the use of purification. This meant that, in order to complete a chemical clean of the system, we would need to i) refill the system and ii) be able to place purification in-service. This ruled out the use of the Over Poisoned GSS as the shutdown guarantee for the unit. With the Over Poisoned GSS not available for a chemical clean, an alternate GSS was required.

The only three alternate GSS's available, none of which were approved for use at the time, were:

- Refill the Moderator System with light water (H_2O) and rely on the H_2O as the neutron absorbing poison.
- De-fuel the reactor
- Implement a Rod Based GSS (RBGSS) where the Shutoff Rods (SA's), Control Absorbers (CA's) and Adjuster Rods (AA's) are guaranteed in core.

The rod based GSS was selected as the most desirable option. In obtaining approval for RBGSS, there were a number of areas that needed to be addressed. These included:

- Sub-criticality margin under all credible accident scenarios
- Integrity of the actual GSS field devices
- Training of involved station staff (including procedure details)

7. Reactivity Management for restart

Unit 7 would normally go critical with 0.95 ppm of poison (Gd in solution) in the moderator, or the equivalent of 25.8 mk of negative reactivity (1 ppm is equivalent to 27.2 mk). With the adjuster rods worth 15.7 mk, their withdrawal would provide a total of ~41.5 mk of negative reactivity that could be removed to offset deposited Gd. As mentioned previously there could have be enough Gd oxalate deposited in the neutronically important region of the core to prevent criticality (in excess of 41.5 mk). This talks to whether or not the unit "could" go critical. It does not speak to whether or not the unit "should" go critical. As a result, it was necessary to review the reactor safety implications associated with deposited Gd oxalate to determine if there were any restrictions that would preclude taking the unit critical with less than 41.5 mk of reactivity worth of deposited Gd.

There were three possible scenarios that could lead to a reactivity management event due to the presence of Gd oxalate being deposited both in and out of core. They were:

- Gd oxalate that was deposited out of core could result in a <u>negative</u> reactivity insertion should it come loose and go in to suspension/solution.
- Gd oxalate that was deposited in core could result in a <u>negative</u> reactivity insertion should it come loose and go in to suspension/solution (deposited Gd is only about 60% effective as a neutron absorber as Gd that is in suspension/solution).
- Gd oxalate that was deposited in core could result in a <u>positive</u> reactivity insertion should it come loose and re-deposit on out of core components (a net removal of –ve reactivity).

8. Clean up in rod based GSS

Prior to restart the calandria had to be refilled. The original water had to be cleaned up to remove the dissolved CO_2 and residual gadolinium oxalate. Following the clean-up the water was then redosed with gadolinium. On refill of the calandria a large increase in the gadolinium concentration was seen. This gadolinium was confirmed to be in nitrate and not oxalate form. Apparently the conditions inside the air filled moderator (ozone, nitric acid and broad band gamma "Cherenkov" radiation) had decomposed the oxalate. Once the refill was complete the RBGSS was applied.

The observed return of gadolinium during and after refill provided hope that the core would be clean enough to go critical without chemical cleaning. To help determine the remaining concentration of gadolinium plated-out in core a pseudo-approach to critical was performed in RBGSS. Chemistry sampling results and the reactor power profile obtained during the poison pull, indicated that there was little or no deposited gadolinium remaining in core.

After all the gadolinium had been removed, a series of equipment configuration changes were executed. The intent of these alignment changes was to ensure a minimum potential for having mobile gadolinium in the system. Following the completion of the tests the station was confident that there would be no major changes in gadolinium concentration due to system configuration changes (Figure 7).

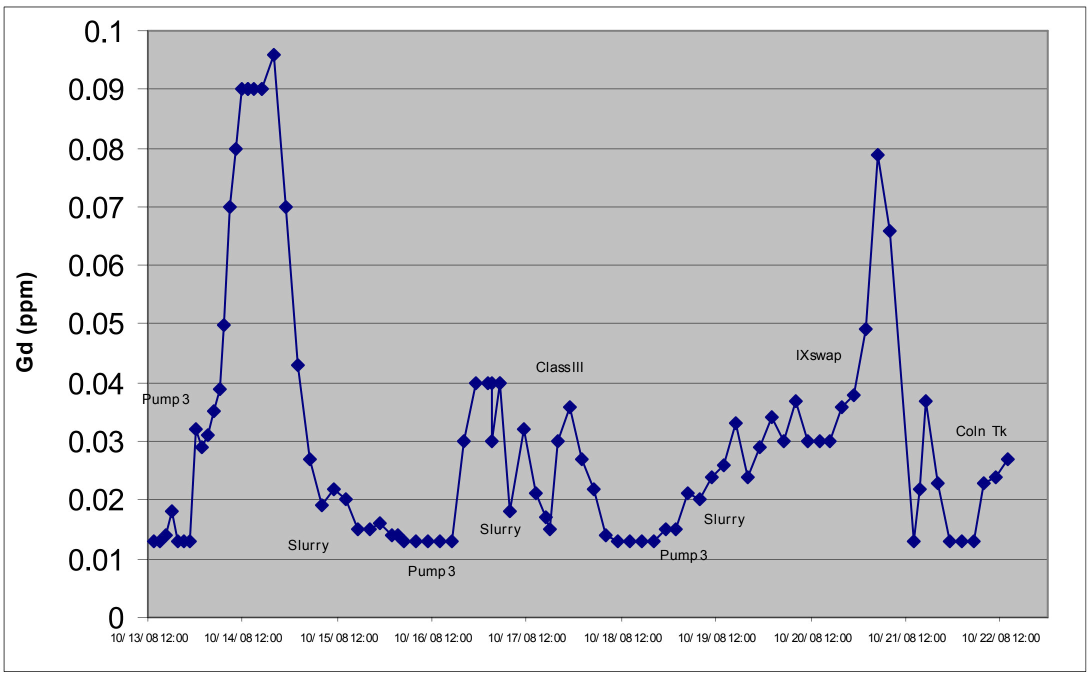


Figure 7 Release of gadolinium following equipment configuration changes

9. Reactivity control for final approach to critical

It was recognized that there remained some uncertainty, with respect to Gd behaviour, and there was a possibility that some undetected deposited Gd remained.
The results of the assessment demonstrated that the only credible events which could be impacted by either the initial distribution of Gd deposits and/or Moderator System perturbations were:

- Loss Of Reactivity Control (LORC)
- Moderator System failures
- Electrical failures (unit specific and/or common mode)

- In Core LOCA
- Seismic Event

The assessment demonstrated that there was adequate trip coverage with up to 5 mk reactivity worth of deposited Gd in core. This required that the following compensatory actions be credited prior to GSS surrender, in support of the ATC evolution and low power critical operation:

- SDS1 & SDS2 Absolute Log N TSP's reduced from 1% FP to 0.2% FP
- SDS1 & SDS2 HTLP trips enabled (an absolute HTLP trip was established)
- HT to remain cold

To ensure that criticality was achieved within the 5 mk reactivity limit, two back out conditions, based on Gd concentration, were built into the Operating Memo that was issued in support of the ATC.

1) The first was to predict, at ~1 ppm of dissolved Gd, if criticality would be achieved with a Gd concentration greater than 0.80 ppm. This was the minimum permissible Gd concentration in the moderator at criticality, with up to 5 mk of equivalent Gd oxalate deposited in core.
2) The second back out was just prior to starting the last poison pull, when the Gd concentration at criticality was estimated to verify that it met the accepted criteria of >0.80 ppm (with an AZL of ≥50% at criticality).

The final approach to critical demonstrated that <5 mk worth of gadolinium was deposited in the core. Start-up proceeded without the need to hold and burn off gadolinium. Subsequently there have been no incidences of unexplained zone level changes due to release of gadolinium oxalate from excore surfaces or equipment.

10. Summary

The successes of this project were largely due to the assignment of dedicated recovery team and responsible senior management. Detailed plans were formulated and resources could be accessed and assigned as required. The project was broken into small pieces which were completed by staff with expertise in that area. Management obtained commitments from each organisation and tracked them tenaciously.

To help ensure timely detection and appropriate actions are taken, specification limits were placed in dissolved CO_2 (TIC) and covergas CO_2. OPG's Chemistry, Metallurgy & Welding Department, ESD, are implementing these across the OPG nuclear fleet. They will also interface with the CANDU Owners Group (COG) on the recommended Action Levels for all CANDU units worldwide.

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