Future Plans for Performance Analysis and Maintenance/Inspection Optimization of Shutoff Rods Based on the Case Study of Bruce Power Unit-3 Shutoff Rod 5 Inspection

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Abstract

Shutdown System 1 (SDS1) is a preferred method for a quick shutdown of nuclear fission process in CANDU® (CANada Deuterium Uranium) reactor units. Failure of a routine SDS1 safety test during Fall 2009 outage resulted in the need to develop and execute a new methodology for Shutoff Rod inspection and re-evaluate the known degradation mechanisms and failure modes. This paper describes the development of this methodology and the obtained results. It also proposes several alternative solutions for the future performance analysis and maintenance/inspection optimization for SDS1 Shutoff Rods based on the Bruce Power Unit-3 Shutoff Rod 5 case study.

1. Introduction

In a normal nuclear operations lifecycle, it is often necessary to shut down the reactor for maintenance, due to a surplus of electrical power on the market or to prevent the release of radioactive material to the environment following a reactor transient or power excursion. Shutdown System 1 (SDS1) is a preferred system for a quick shutdown of nuclear fission process in situations when certain neutronic or process parameters exceed their acceptable limits. Shutdown System 1 at Bruce Power Units 1-4 consists of 30 mechanical Shutoff Rods that are vertically inserted into the core following a trip signal. The rod clutches are normally energized when the rods are poised. Once the rod activation is required, the power supply to the clutches is interrupted and the rods gravity-drop into the core assisted by compression spring tension. A reactor unit cannot be operated with Shutdown System 1 out of service. There is also a restriction on how many rods can be declared unavailable during on-line operation before the system is taken out of service and the unit is forced to shutdown.

This paper describes a condition of Shutoff Rod 5 (SOR-5) on Unit-3 of Bruce Power Nuclear Generating Station (NGS) that was discovered following a failure of a routine safety test and subsequent inspection of the rod and its guide tube in-situ.

2. Routine system safety testing

In order to ensure that sufficient negative reactivity can be added to the reactor in time to safely shutdown the nuclear fission process Shutoff Rods are routinely tested, both on-line and during reactor shutdowns.
A routine partial rod drop test (SST1.00) is performed on-line on a group of 3 rods every 10 days, one rod at a time in order to confirm the so-called freedom of movement, i.e. to ensure that the drop relays will open their contacts and interrupt power supplies to the clutches on a trip signal. The rods drop in core up to approximately 14%, which confirms rods' availability but does not introduce sufficient amount of negative reactivity to create flux tilts on a running unit.

A full rod drop test (SST1.19) is typically performed when the reactor is in GSS or OPGSS (Guaranteed/Overpoisoned Guaranteed Shutdown State) with the power levels below 10^{-3} F.P. (Full Power) when the calandria is full with the level greater than 8060 mm and Shutdown System 2 poised. The test is performed on all rods simultaneously. The insertion speed is measured against the three pre-set timing gates. The drop time of the rods is plotted using the data collected by the Computer Technicians and is analysed to ensure that the drop profile curve remains to the left of the timing gates, thus indicating that the rods pass the test. This test confirms that all rods completely drop into the core within the prescribed timing requirements.

3. Performance trending and first signs of degradation

Full rod drop SST 1.19 performed on 07 November 2008 indicated that SOR-5 performance deviates significantly from the rest of the rods. Degradation continued, as shown in SOR drop tests up to 24 September 09. This performance trending is shown in Figure 1 below. As shown, the rod performance in 2007 test was acceptable and within the expected range. With the time progression, the SOR-5 rod drop timing and profile has changes significantly, until the test conducted on 24 September 2009 resulted in the test failure and produces an unusual profile with a clearly defined "hump" at about 80% in-core.

During the Fall 2009 outage, the as-found full rod drop test showed SOR-5 dropping normally up until about the 60-70% in-core, where SOR-5 was slowing down, as if the rod's travel was being impeded by some blockage. The test was repeated 3 more times with similar results.

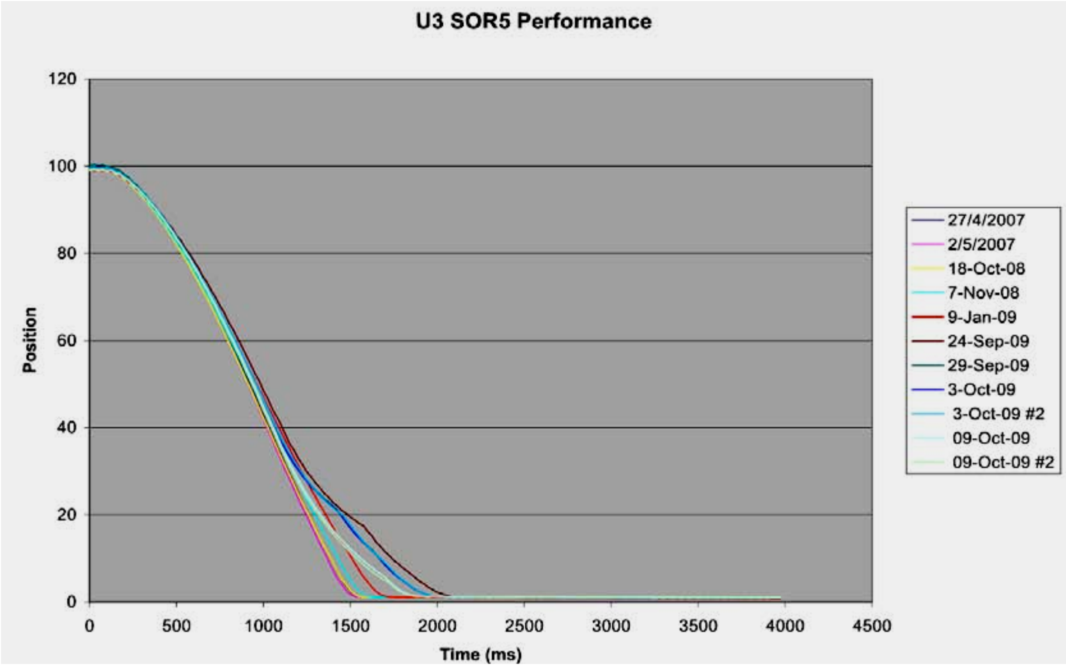

Figure 1: Unit-3 Shutoff Rod 5 (SOR-5) performance historical trend. Plot is comprised used full rod drop test (SST1.19) data for the period between 27 April 2007 and 09 October 2009.

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4. Initial troubleshooting and mitigating actions

Following a discovery of the SOR-5 failure, an initial troubleshooting was conducted in order to determine the possible cause of failure. First, SOR-5 Logic unit was replaced as the slow rod performance was originally attributed to an incorrect position indication or calibration problem. The subsequent drop test was performed to determine whether this eliminated the fault, but showed small improvement in time to reach the third timing gate.

Next, SOR-5 Potentiometer was replaced and the full rod drop test repeated, with no improvement in performance.

Next, SOR-5 mechanism was replaced with a new mechanism and tested twice on 09 October 2009. The two full rod drop tests passed, though SOR5 passed with a small margin.

Also, and perhaps most important, oil debris were discovered on the acceleration spring on the top of SOR-5. This indicated that there may be a different degradation mechanism affecting the rod performance present than it was first thought and a decision was made to conduct a comprehensive inspection of the rod element as well as the guide tube to determine whether the degradation of the rod performance could be attributed to the presence of a blockage or foreign material contamination. As the rod housings are located on the top of the Reactivity Mechanism deck and are not easily accessible while the units are at power, this project was scheduled for execution in Spring 2010 planned outage so that sufficient time and resources could be properly planned and allocated.

5. Past experience

Although there is a limited past experience with rod inspections at Bruce Power, none have been performed on an operating unit in OPGSS with the calandria full and the core recently fuelled. Previous inspection on SOR-10 in Unit-2 was conducted by AECL (Atomic Energy of Canada Ltd) in 2009 for the rod locator bracket displacement [1]. This inspection, however, provided a good bench-marking data for the expected rod and guide tube degradation patterns and imperfections. For example, a variety of surface features such as discolouration, stains, scratches and abrasions were found during the 2009 inspection. None of those were found to be penetrating deeper than the external cladding and presented no risk to the rod operation. Therefore, similar signs of wear and tear would present no concerns if found on SOR-5.

Following the full rod drop tests conducted in the Fall 2009 outage and the unsatisfactory results of the initial mitigating actions a need for a new approach to SOR-5 performance improvement was clearly identified. It became obvious that the previous operating experience and assumptions for the rod conditions were not correct or did not include all of the potential failure mechanisms. Thus, it was decided that a comprehensive inspection was required in order to determine the extent of condition and develop a set of mitigating actions. However, at the time of the scheduled SOR-5 inspection, there was no previous experience of a project of this nature. The project sequence and associated work coordination package had to be developed based on Engineering and Maintenance personnel assumptions and best industry practices. This was a high risk evolution that required considerable preparation and planning as discussed in the following section.

6. Rod inspection methodology

During the Spring 2010 outage a visual inspection of the SOR-5 guide tube and rod element was performed by a joint team of Bruce Power and AECL (Atomic Energy of Canada Ltd) specialists. This required a comprehensive work package to be developed, which included the Foreign Material Exclusion plan, Inspection procedure, contingency plans and work package organization and contract support from various stakeholders. Although an inspection of SOR-10 on Unit-2 had been previously performed, it was done with an empty calandria and no fuel present in the core. In the case of Unit-3, a methodology for such an inspection had to be developed for the reactor in OPGSS with a full calandria and recently fuelled core. Listed below are some of the main requirements that had to be addressed during the project preparation stages:

- For the purpose of this inspection an approximate 125 cm^2 hole had to be created when SOR-5 mechanism and the rod are removed. This hole creates a breach in the moderator system to the outside of containment which requires a comprehensive ALARA (As Low As Reasonably Achievable) plan to be develop to minimize the radiation exposure to the personnel and equipment. It also requires that no simultaneous work can occur with other Moderator systems as it could potentially produce a direct path from inside containment to outside containment. It was determined that in the event of an upset, the moderator system will be closed as soon as possible and no later than 10 hours to limit the release of moderator fluid.
- The FME/Shielding cap (Foreign Material Exclusion/Shielding) had to be fabricated to be installed on the SOR-5 and the adjacent viewing port on the Reactivity Mechanism (RM) deck. This fixture is designed to prevent FME event and to reduce the amount of tritiated air coming out of the guide tube.
- In addition, supporting permitry required that SDS2 (Shutdown System 2) had to be blocked during this inspection. The reactor unit must be in OPGSS and SDS1 available, with the exeption of SOR-5, during this project.
- Remote video inspection using a radiation tolerant camera has to be performed rather than a conventional visual inspection due to the anticipated radiological hazards. A viewing work station has to be set at a safe distance and equipped with communication lines and recording equipment.
- The resolution capability of the inspection camera should be at least equivalent to that obtainable by direct visual inspection. Also, the mimimum light intensity at the examination surface should be 100 footcandles (1000 lux) and the light level verification should be documented. Inspection Camera Support Sleeve that encapsulates inspection camera has to be equipped with independent retrieval cables.

It is important to note that “visual inspection” terminology used in this paper refers to the remote-controlled camera positioned on the deck with the inspection personnel monitoring the progress and analysing the data from a distance in order to minimize the radiation exposure. R93 radiation tolerant camera for the interior surfaces was selected as the primary equipment to be used for the visual inspection of the SOR-5 guide tube. The inside surfaces of the upper and lower guide tube, welded joints, and the top and the bottom of the guide tube were viewed with the axial camera head during the inspection.

There are certain limitations inherently associated with the proposed camera inspection of the guide tube that have to be taken into consideration while analysing the results. For example, certain flaws or damage may not be noticed, however it may be one of the contributing causes to the SOR-5 performance degradation, e.g. straightness, concentricity, bow, etc. may have a direct impact on the rod drop profile and speed of insertion as it is necessary to maintain the nominal design clearance between the SOR and the guide tube.

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This project started with removal of the grating on the deck. Next, SOR-5 mechanism was lifted off in order to gain access to the rod. This allowed performing a visual inspection of the top of the rod assembly, which revealed a considerable amount of foreign material, believed to be irradiated oil residue, present all over the rod (i.e., oil flakes, globs). This is shown in Figure 2 (a) below, where the top of the SOR-5 assembly is shown.

(a) **(b)**

Figure 2: (a)The top of SOR-5 assembly is shown, where a clear sign of foreign material contamination can be seen on the top of the rod element and the guide tube exterior; (b) Top of SOR-5 rod, where solid debris are visibly present.

Next, the rod absorber element, consisting of outer layers of stainless steel with an inner layer of cadmium forming a hollow tube was craned out of the guide tube and positioned in suspension inside the reactivity management flask. The top of the rod is shown in Figure 2 (b) where the presence of solid foreign material is also clearly visible. As the rod was being lifted, the rod condition was recorded and initial visual inspection was performed. As shown in Figure 3 (a) below, there was significantly less debris present on the middle portion of the rod.

(a) **(b)**

Figure 3: (a) Middle section of SOR-5 - normal wear and tear is present; (b) Lower portion of SOR-5- a significant amount of foreign material buildup is present.

When the rod was completely lifted out, it was noted that the last 3-4 inches of the rod appeared to be completely covered by a rust colored residue as shown in Figure 3 (b). Furthermore, once the rod was placed into the flask, the inspection revealed that the ID (inside diameter) of the rod was contaminated with the rust-colored material as well.

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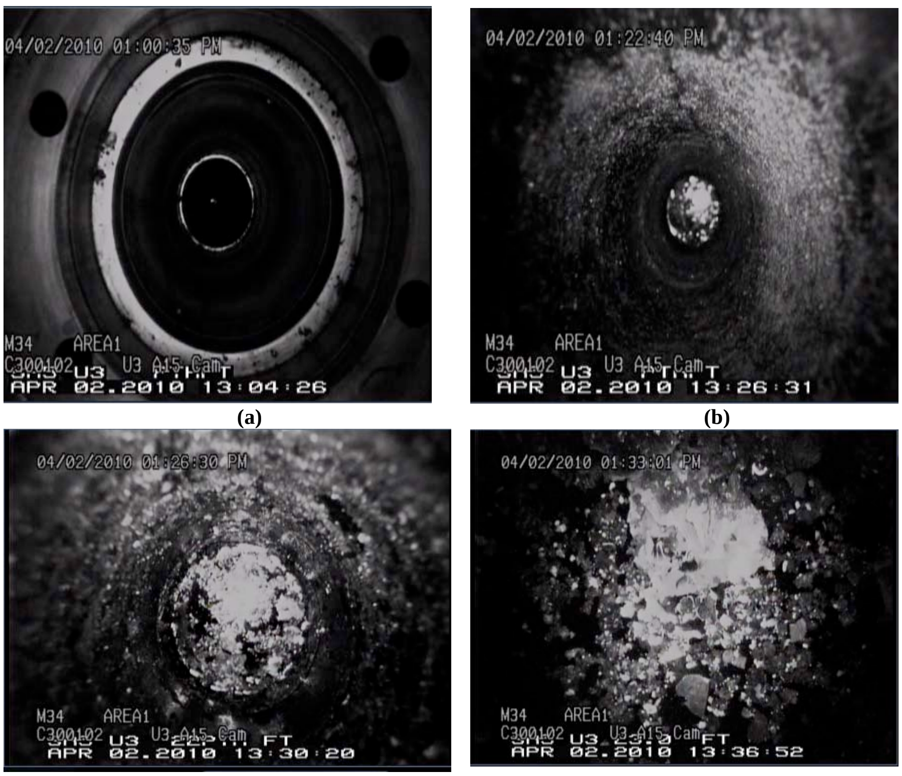
Next, SOR-5 guide tube inspection was conducted. A downward looking camera was inserted into the guide tube up to the moderator level as shown in Figure 4 (a). The camera died in a few seconds once it past the first set of guide tube holes. It appears that the radiation coming through the holes was greater than the 2 million REM limit of the camera. The first video shows that the guide tube is clean until about 3-5 feet from the moderator level (as shown in Figure 4 (b)). At that location, a similar excessive build-up of crud that was seen at the last 4-6 inches of the SA5 rod's bottom. In addition, there was a layer of oil crud floating on top of the mod D2O, covering almost 50% surface area, consisting of small flakes, and 2-3 big chunks as shown in Figure 4 (c) and 4 (d).



(a) **(b)** **(c)** **(d)**

Figure 4: (a) Downward looking camera was inserted into the SOR-5 guide tube up to the moderator level; (b) At approximately 3-5 feet from the moderator level there is an excessive build-up of crud similar to the one that was seen at the last 4-6 inches of the SOR-5 rod's bottom; (c)&(d) A layer of oil crud floating on top of the mod D2O, covering almost 50% surface area, consisting of small flakes, and 2-3 big chunks.

Once the camera passed through the moderator level, the image quality suffered, due to the water and crud until at the guide tube perforations (holes) level the camera burnt out in a few seconds. It appeared that the radiation coming through the holes was greater that the 2 million REM limit of the camera. A second camera, typically used for reactor maintenance at Bruce Power, was obtained. This camera had lower image quality, but was shielded in a metal cylinder and was expected to last longer so that a second inspection could be conducted in order to obtain further data and have a means of verification.

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Once the guide tube inspection was complete, the rod assembly was replaced and post maintenance testing was conducted by the means of a full rod drop test (SST1.19). As shown below, the SOR-5 (light yellow) was still showing an unusual drop profile and tracking slower than the rest of the group.

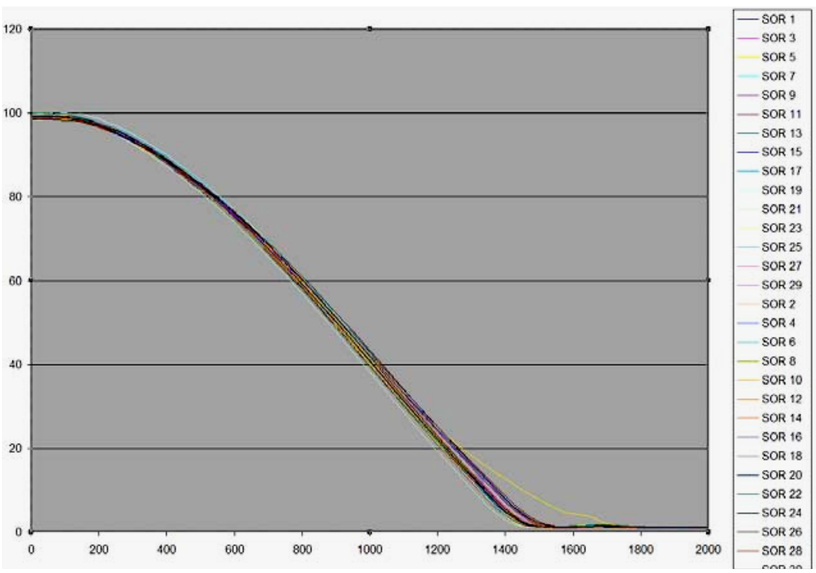

Figure 5: A full rod drop test performed on 04 April 2010 for post-maintenance testing and verification following the SOR-5 rod and guide tube inspection. SOR-5 is still showing an unusual drop profile and tracking significantly slower than the rest of the group.

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7. Material analysis

During the camera inspection of SOR-5 guide tube, two of the largest solid pieces were retrieved from the surface of the moderator. These samples are shown in Figure 6.

Figure 6: Two pieces of solid material floating on the open surface of the moderator were retrieved for material analysis. As shown, there is a variation in color, thickness and texture of the samples.

As can be noted from Figure 6, the two samples vary in color and texture as well as in thickness and brittleness of the material. The lighter-coloured sample on the right is significantly thicker and has a texture of a gum-like material, very much like a gummy-bear type of a jellied substance. The darker-coloured material on the left is much thinner and significantly more brittle.

A portion of the samples was pyrolyzed at about 750C. The pyrolysate was examined as a thin film condensate on a KBr (Potassium Bromide) disk by Fourier transform infrared spectroscopy (FTIR: Thermo Nicolet Nexus 470 SN 2620 instrument). The resulting spectrum was examined for major spectral features and also compared with commercial spectral libraries. Based on this examination the material was identified as a hydrocarbon, similar to many lubricating oils with some oxidation being evident.

Another portion was ground with KBr in a mortar and pestle to examine the structure of the polymerized form. An FTIR Identification by Fourier Transform Infrared spectrum was obtained and examined as above. The spectrum indicated that the oxidized portion was inherent to the sample and not an artifact caused by pyrolysis. Comparison with commercial materials indicated a similarity to hydrocarbon resins with aliphatic linear, branched and cyclic structures. There was also indication of some free water trapped in the material [2].

8. Discussion of results

As previously discussed in Section 5 - “Past Experiences”, the inspection performed in Spring 2010 outage showed no significant signs of wear and tear that might be a causing factor for the SOR-5 performance degradation. There were no imperfections of cadmium corrosion, no damage of weld seals, cracks or gross deformation of the main parts of SOR-5 assembly present.

The material analysis of the samples identified this foreign rusty-coloured substance as hydrocarbon resins with aliphatic linear, branched and cyclic structures, similar to many lubricating oils, although an exact match to a commercial product brand or type could not be made. These observations were consistent with the known history whereby some oil was inadvertently released into the Unit-3 moderator. The main finding of the inspection was the confirmation for the presence of foreign material on the surfaces of the guide tube and external and internal surfaces of the rod absorber, which had not been previously witnessed or analysed.

Nuclear safety analysis was conducted to assess the safety impact of the slow Shutoff Rod 5 (SOR-5) and concluded that the slow rod performance has no impact outside the large break LOCA (Loss of Coolant Accident) [3] mainly based on the fact that the rod does meet the first two timing gates.

Based on the analysis of SOR-5 performance from November 2008 to October 2009, the rate of slowing of SOR-5 at the third gate decreased with time; therefore based on the short period of time that Unit-3 is required to run until its next planned outage the performance was deemed to be unlikely to deteriorate significantly. It is expected that SOR-5 may marginally fail its drop test in the next outage, but it is very unlikely that its performance will decrease significantly.

9. Future Work

Although the safety analysis concluded that the SOR-5 poor performance is acceptable [3] from a nuclear safety standpoint, there is a clear need to develop a methodology for future SOR-5 cleaning/replacement in order to improve its performance and ensure a reliable operation for the Bruce A Unit-3 life extension project. Therefore, an Engineering intervention is required in order to return SOR-5 to the acceptable level of performance.

9.1 Proposed methodology for SOR-5 rod element clean-up

One of the proposed alternatives for future work is to use a dry ice blasting method for SOR-5 rod absorber element clean-up. The main advantage of dry ice blasting is that it is very gentle, almost like snow, and leaves no cleaning residue. Therefore, for this alternative it is possible to develop a work package where the rod absorber element is lifted up into a plastic tent connected to the active exhaust ventilation system. Any tritiated vapors will be ventilated and off-gassed while the solid residue will be collected inside the plastic tent. The ice blasting will be conducted inside the tent and will leave no residue or corrode the rod element surface. Once the rod is dried up, it could be lowered down into the guide tube into its normal position. The work progress can be monitored real-time using several cameras positioned inside the tent and all steps can be recorded for future analysis.

Alternatively, a mechanical tool can be designed for the rod cleanup. The tool will be created using a typical bottle cleaning brush concept and connected via a flexible long handle to a small-size, e.g. ½ HP motor, which speed/rotations can be controlled by a variable frequency inverter (VFI). The brush will rotate around and inside the guide tube and scrape the solid build-up of oil off the exterior and internal surfaces. This process, again, will take place inside a plastic tent with the active exhaust ventilation and will be remotely monitored over a video link. The brush speed/rotation/angle can be adjusted so that an optimal contact is made with the rod surface.

9.2 Proposed methodology for SOR-5 guide tube clean-up

Currently no methodology exists for the in-situ guide tube clean-up. It is important to remember that most of the surface buildup is present on the internals of the guide tube just above the moderator level. Thus, foreign material control is absolutely paramount as this task has to be performed on a working unit in OPGSS. No additives or chemical residue can be introduced into the moderator as well as no particulate or foreign substance can be left inside the guide tube itself.

Also, one of the main constricting factors in developing this methodology is the significant radiological hazards associated with work on the open moderator systems. During the Spring 2010 inspection, the dose rates to the reactor maintenance personnel performing work on SOR-5 mechanism replacement showed that dose rates up to 14 mrem were experienced. This dose was recorded for the craning and repositioning of the SOR-5 mechanism and does not include the projected exposure for direct contact or work in close proximity to the open guide tube.

9.3 Alternative solution – replacement of SOR-5 assembly

An ultimate solution to the condition of the SOR-5 and the challenge of developing a clean-up methodology may be to replace the entire guide tube and the rod element assembly. This alternative, however, has its own specific challenges, such as significant cost of the components and a long lead time required to custom fabricate a new guide tube and rod element. The installation of the guide tube will require threading/tension adjustment to be performed at the bottom of the guide tube to ensure it is properly attached to the bottom of the calandria. It will also require in-situ welding and pressure boundary testing to be performed following the installation to ensure the assembly position and structural integrity.

Also, the installation of the guide tube and the new rod has to be performed on a working unit, thus the same radiological hazards that were discussed in the previous section will have to be addressed. Even if moderator drain is performed in order to aid in this task, the radiation beam coming from the open SOR-5 guide tube will most likely require that all contact work is performed using robotic or remote-control tooling.

10. Conclusions

The degraded performance of SOR-5 in Unit-3 of Bruce Power NGS has created significant maintenance, operational and engineering challenges and poses a risk to the safe, reliable operation of the units. This paper describes the background events leading to the need for a comprehensive SOR-5 inspection that included removal of the rod element and in-situ visual inspection of the guide tube internals up to 48.5 ft down the calandria vessel. The results of such inspection performed in Spring 2010 outage revealed that the degraded rod performance was caused by the presence of irradiated oil build-up on the surfaces of the rod absorber element as well as the internal surfaces of the guide tube.

This presented a new and an analyzed degradation mechanism for the Shutdown System 1 that had not been experienced before. It also raised the need for a new methodology for future inspections to be refined based on the SOR-5 experience as well as the need for a new method and tooling to be developed for this and similar occurrences in the future.

11. References

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[2] A. Rudolph, "Material Analysis Report", Information Copy: 10-01753, 2010/05/28
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