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IMPROVEMENTS IN IN-BAY IRRADIATED FUEL INSPECTION PLANNING & ANALYSIS AT BRUCE POWER

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ABSTRACT – This paper describes improvements in irradiated fuel inspection planning & analysis implemented at Bruce Power since 2012. A review of inspection plans and fuel performance reports since 2001 identified significant variations in how irradiated fuel bundles were selected for inspection from year-to-year. A series of inspection tasks was established in an inspection logic and technical basis document. Inspection objectives and bundle selection criteria were defined for each task. These requirements, along with resource availability are now used to prepare a fuel inspection plan each year. The inspection results are then considered in the context of the analysis objectives for each task. The inspection results are presented in brief monthly updates and in-depth semi-annual reports in addition to the Annual Fuel Performance Reports. These changes have improved the effectiveness, consistency and efficiency of Bruce Power's fuel performance monitoring.

1. Introduction

Bruce Power monitors fuel performance to support the internal equipment reliability program [1] and to fulfill CNSC requirements [2].

In the Irradiated Fuel Bay (IFB), a representative sample of irradiated fuel bundles is visually inspected. The visual inspections identify issues with fuel performance (including defective fuel elements, excessive wear and deformation, etc.) or confirm that fuel performance was acceptable. Fuel is inspected each year to monitor changes in performance related to changes in the fuel design, fuel manufacturing and reactor operation (including reactor aging).

Fuel performance issues are fed back to the fuel manufacturer, the fuel design authority and operations, as appropriate. These stakeholders take action to address significant fuel performance concerns and ensure the continued reliability of fuel.

A summary of fuel operating conditions, design & manufacturing, inspection results, fuel defects and additional information is compiled in Annual Fuel Performance Reports (AFPRs) and submitted to the CNSC. CNSC staff use these reports to provide an assessment of fuel performance and licensing compliance which is used as input into the annual CNSC Staff Integrated Safety Assessment of Canadian Nuclear Power Plants [3].

Since 2012, Bruce Power has undertaken a number of initiatives to improve the fuel performance monitoring program.

2. Inspection Planning

The Bruce A and Bruce B reactors each discharge approximately 5,500 bundles per year (for a total of 44,000 bundles per year across the eight units). The fuel performance monitoring program can only support the inspection of a fraction of these bundles. From 2010 to 2012, between 350 & 550 bundles were inspected each year. As a result, choosing which bundles to inspect is critical to success of the program.

A review of inspection plans and fuel performance reports since 2001 identified significant variations in how irradiated fuel bundles were selected for inspection from year-to-year. To reduce these variations, Bruce Power documented the Irradiated Fuel Inspection Logic and Technical Basis [4].

Bruce Power also prepares a plan each year to identify how many bundles associated with each irradiated fuel inspection task will be inspected that year.

2.1 Irradiated Fuel Inspection Logic and Technical Basis

The key outputs of the Irradiated Fuel Inspection Logic and Technical Basis are the selection criteria that are used to select the limited number of bundles that are flagged for inspection. To establish the selection criteria, objectives for the fuel performance monitoring program were first defined.

To define the objectives for the fuel performance monitoring program, Bruce Power considered requirements from internal procedures, CNSC guidelines, inspection capabilities, industry guidelines and the past inspections of Fuel from the Bruce units. A guideline published by EPRI [5] was found to be a particularly useful reference. The EPRI guideline emphasized that failed fuel elements must be inspected so that the apparent cause of each fuel failure can be determined and actions can be undertaken to prevent the recurrence of failures. The guideline also stated that the inspection of non-failed fuel is necessary both to support failed fuel investigations and monitor margins in key fuel performance characteristics.

Bruce Power identified the following objectives for irradiated fuel inspections:

1. Monitor typical fuel performance to identify unexpected changes in fuel performance or confirm that there are no unexpected changes in fuel performance
2. Monitor fuel performance in fuel bundles that are operated over or near the operating envelope to confirm the adequacy of the operating envelope
3. Identify all fuel bundle elements that released sufficient fission products to generate an observable increase in the radioisotope activity measurements to determine the root cause of all identified defects
4. Monitor fuel performance during specific operational events or under specific operating conditions
5. Monitor fuel performance following specific manufacturing changes or specific manufacturing events
6. Monitor fuel performance following specific fuel design changes or specific station design changes

Each of these objectives was turned into an inspection task with its own unique bundle selection criteria.

Monitoring typical fuel performance is supported by the Generic Surveillance Inspections task (task code R-GS). Each year, twenty random bundles from each unit are selected for inspection under this task. Random selection means that the bundles are chosen for inspection without consideration to their irradiation history (including channel, occupied positions, bundle burn up, bundle maximum power, etc.). To minimize the burden of fuel inspections on fuel handling operators, R-GS bundles are often selected from irradiated fuel trays that have other bundles selected for inspection on them. There are criteria to ensure that bundles are still randomly selected, including requirements that only one bundle per unit channel per tray can be selected for inspection under this task and that at least 3 bundles discharged from each quarter be selected for each unit under this task.

Monitoring operating envelop fuel performance is supported by the Compliance Inspections task (task code R-CP). All bundles that reach or exceed the bundle power action limits are selected for inspection under this task. These action limits are significantly lower than the 1035 kW maximum bundle power supported by the 37R design [6]. All bundles that reach or exceed a burnup of 350 MWh/kgU are also selected for inspection. Once again the trigger for inspection is well below the maximum burnup of 450 MWh/kgU supported by 37R design. Finally, all bundles that exceed 60 minutes under crossflow conditions will also be selected for inspection. The bundle inspection selection criteria for this task may be expanded in the future to consider additional operating parameters.

Identifying and assessing the cause of defective fuel elements is supported by the Defect Inspections task (task code R-DF). All bundles in a channel fuelled due to suspected defects are selected for inspection under this task. If the elements can be confirmed to be defective before all of the bundles are inspected, then the rest of the bundles do not need to be inspected. The apparent cause of the defect is then assessed. Some defect mechanisms can be identified from only the first set of visual inspection results (inc. debris fretting defects and vibration fretting defects). Other defect mechanisms can only be identified after further inspections, including disassembly or even hot cell Post Irradiation Examinations (PIE).

Monitoring fuel performance related to operations is supported by the Operational Emergent Event series of tasks (task codes O-EE##X). There are both large long term tasks and small, short term tasks in this category. In the long term category, there are two tasks related to the acoustic endplate cracking that is observed at Bruce B. The objective of the first task is to monitor the rate of endplate cracking in Bruce B acoustic channels. This is accomplished by selecting all bundles discharged from the most active acoustic channels for inspection and a sampling of other bundles from other channels and units. The goal of the second task is to identify any Bruce B channels that are discharging bundles with endplate cracks that are not currently included on the acoustic channel list. This task was structured to select bundles from the higher risk channels annually and select bundles from all of the remaining outer zone channels on a less frequent basis.

Since the inspection logic and technical basis was issued in April 2012, there have been 8 smaller, short term tasks initiated under the Operational Emergent Event category. Some of these tasks were created to respond to other inspection results. Two examples are a task to inspect additional bundles from units 1 & 2 for inspection following the discovery of deposits on the bundles and a task to inspect additional bundles from a channel where an unusual defect was found. Other tasks were issued following an operational event, including a task to inspect a limited number of bundles following a Loss of Class IV power event. Lastly, some tasks were created as a result of issues identified with interfacing systems. The best example of this is a task that selected bundles for inspection if they were adjacent to shield plugs that were found to be only partially locked or unlocked following the return to service of Units 1 & 2.

Monitoring fuel performance related to manufacturing is supported by the Manufacturing Emergent Event series of tasks (task codes M-EE##X). To date there have only been two tasks contemplated under this category. A task was issued to inspect a limited number of bundles that were loaded with Laser-Etched barcodes on the sheaths on select elements. This change to the bundles was not a design change, but instead a change allowed within the manufacturing tolerances of the existing design. Another task will be issued in the future to inspect the first bundles that are discharged that were manufactured by the new automated manufacturing line at Cameco Fuel Manufacturing. The automated line represents a significant change to the manufacturing process, but no significant impacts on fuel performance are expected.

Finally, monitoring fuel performance related to fuel design changes is supported by the Design series of tasks (task codes D-XXX). The first task issued under this category was issued to inspect bundles from unit 3 following West Shift Plus. The bundles that were most likely to experience increased vibrations as a result of the change have been selected for inspection. A task to inspect the first 37M bundles exposed to typical operating conditions has also been issued. This task includes a requirement to disassemble a limited number of bundles so that any differences in wear of the centre element can be observed.

The requirements for the inspection tasks that require a large number of bundles to be inspected over a number of years are written into the Irradiated Fuel Inspection Logic and Technical Basis. The smaller inspection tasks are defined in a standard form. Regardless of where the task is defined, in addition to the objective and bundle selection criteria, the following information is also documented:

- A standardized code for the inspection task
- The number of bundles & serial numbers of bundles to be inspected, if available
- The task closure requirements and the target date for completing the inspections
- A description of the analysis that must be performed on the inspection results

While the number of bundles that are selected for inspection each year is somewhat variable, this structure allows for the prediction of long term inspection requirements. Key variables include the number of outage days for each unit and the emergent events that come up each year. The table that is used to establish a long term estimate for bundles selected for inspection at Bruce Power is shown in Table 1, below.

Type	Inspection Objective	Task Code	Estimated Number of Bundles to Select for Inspection	
			Bruce A	Bruce B
Routine	General Surveillance Inspections	R-GS	#	#
	Compliance Inspections	R-CP	#	#
	Defects Inspections	R-DF	#	#
Operations	Acoustic Channel Monitoring Inspections	O-ACM		#
	Acoustic Channel Locating Inspections	O-ACL		#
	Operational Emergent Inspections	O-EE##X	#	#
Mnfctrng	Manufacturing Emergent Inspections	M-EE##X	#	#
Design	Design Emergent Inspections	D-XXX	#	#
		Total	#	#

Table 1 Estimated Annual Number of Bundles to Select for Inspection by Objective

2.2 Annual Irradiated Fuel Inspection Plans

The irradiated fuel inspection logic and technical basis establishes the criteria that are used to select bundles for inspection. The individual bundles that have been selected for inspection are tracked on a master list of fuel to inspect. Typically bundles are added to the list of fuel to inspect as they are discharged[1]. To allow for continuous inspections, it is desireable to maintain around 50 bundles on the list of bundles to inspect.

The backlog of bundles to inspect can grow to significantly higher levels if there is an increase in the number of bundles selected for inspection (i.e. if there is a defect excursion) or if there is a decrease in the rate of inspection (i.e. due to inspector and fuel handling operator availability or equipment issues). Typically, the number of bundles expected to be selected for inspection in a year does not match the predicted inspection capacity. As a result, a plan to manage the execution

[1] Bundles inspected under the general surveillance inspections task are a notable exception. They are typically added to the list of fuel to inspect once a quarter.

of the inspection program is necessary. An Irradiated Fuel Inspection and PIE plan is issued on an annual basis [7].

The plan first establishes the size & composition of the fuel inspection backlog at the beginning of the year. The plan then estimates the number of bundles that will be selected for inspection in the following year. These two ingredients establish the number of bundles that are required to be inspected during the year.

The plan then estimates the inspection capacity for the year. The inspection capacity is based on the expected personnel and equipment availability for the upcoming year. Typically, the inspection capacity is less than the inspection requirement. The plan then prioritizes the inspections to actually complete during the year. Defect inspections are typically given top priority. General surveillance inspections (especially of bundles that were discharged in previous years) are usually given lowest priority. The actual completed inspections are then monitored against the planned inspections throughout the year.

Finally, the plan calculates the projected year end backlog by subtracting the planned inspections from the inspections that are required.

3. Inspection Analysis

The Irradiated Fuel Inspection Logic and Technical Basis and the Annual Irradiated Fuel Inspection Plan ensure that the irradiated fuel bundles of most interest are visually inspected in-bay. The outputs of each inspection are completed inspection sheets, written inspector comments and a series of photographs. The next challenge is to analyze all of the data that is collected. The analysis of the data is broken down into the following three phases:

1. Entry of data into the Fuel Inspection Database (FID) and preliminary review of fuel inspection results
2. In-depth analysis of fuel performance issues & concerning anomalies
3. Summarizing results & analysis for the CNSC and other stakeholders

3.1 Preliminary Review

The majority of inspection results are transferred from the inspectors to the analysts at the end of each month. Significant results, such as defects, endplate cracks, etc are transferred to the analysts soon after the inspections are complete. The analysts enter the inspection results into FID and highlight significant results for further analysis. In 2010 Bruce Power migrated FID from an Oracle based database to an Access based database. This allowed for improved access to the database and improved abilities to query the database.

The analysts also prepare a monthly update. The monthly updates consist of a few tabloid-sized pages and were created to be visual updates. The updates describe the inspection highlights in point form and more importantly include the most significant inspection photos. The updates also include a table that lists the serial numbers of all the bundles inspected and indicates if the inspections include evidence of the known significant fuel performance issues (fuel defects, endplate cracking, etc). A second table is included to report the inspection progress against the annual plan. Finally, some guidance on the inspection priorities for the upcoming month is also provided. A screen shot of a typical monthly update is shown below in Figure 1. The monthly updates are issued within two weeks after month-end.

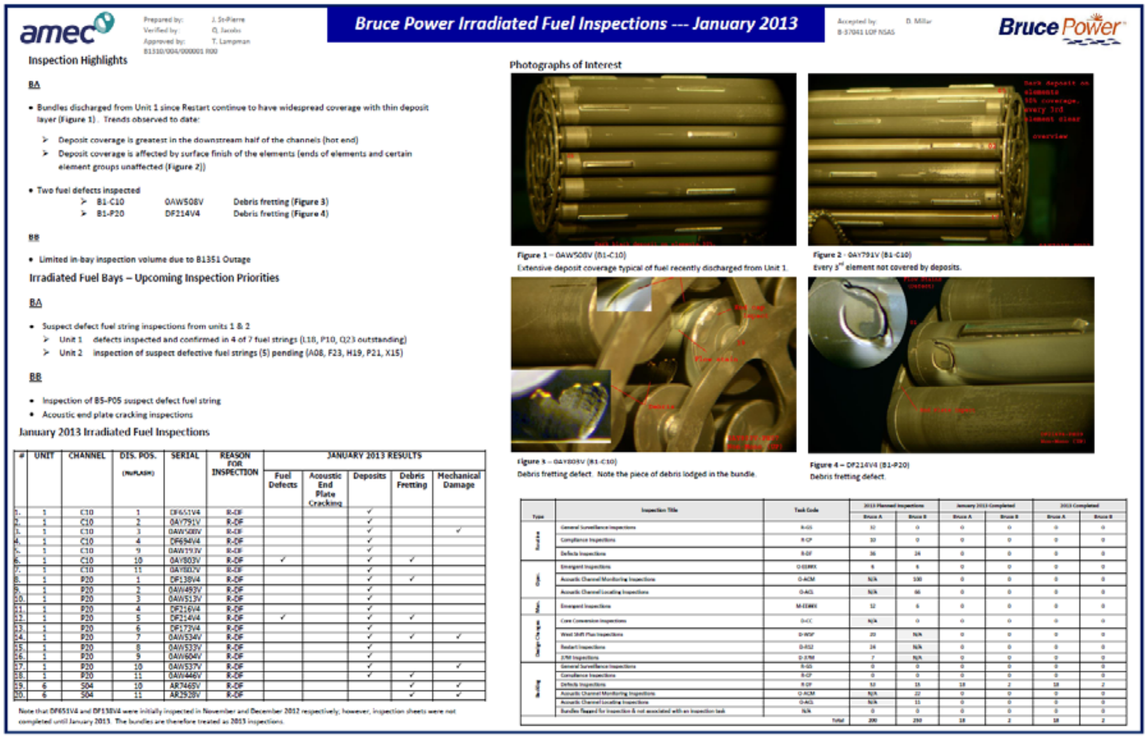

Figure 1 Example of the Visual Monthly Updates (the January 2013 Update) [8]

The monthly inspection updates were first introduced in 2009 but underwent a major reformatting in 2013. The updates are low cost and offer an efficient snap shot of the month's inspection results to be reviewed by the fuel design & performance monitoring engineers. The updates are also an effective way to communicate inspection results to other stakeholders in the organization.

3.2 In-Depth Analysis

The analysts also prepare mid-year and year-end fuel inspection reports [9]. The reports document the detailed analysis of the inspection results. The analysis objectives are directly aligned with the irradiated fuel inspection objectives described in the Irradiated Fuel Inspection Logic and Technical Basis.

Typical fuel performance is analyzed by considering all of the inspection results available. The General Surveillance inspection task ensures that there are sufficient inspection results to support a meaningful assessment of typical fuel performance. Typical fuel performance is assessed in two ways, first by analyzing trends in fuel performance and second by analyzing concerning anomalies.

To analyze trends in fuel performance, thirty six observations of bundle and other component condition have been identified. Table 2, below, lists all of these observations. The percentage of fuel with each of the observations in each of the last five years are plotted to allow for a comparison. Significant changes and high frequency observations are investigated further. The investigations aim to determine the cause of the results and recommend corrective actions when appropriate. Some investigations are documented in separate reports or memos that are later referenced in the semi-annual reports.

Component	Observation
Bundle Condition	Broken End Welds
	Crushed
	Dropped
	Deformation
	Unusual Scrapes
	Bowing
	Interlocked Spacers
	Spacer Pad Gaps
	Oxide / Stain / Deposit
	Sparkled / Speckled
	Black (Dark) Deposits
	Mottled
	Debris
	Debris Fretting
Endplate Condition	Endplate Cracks
	Endplate Mech Damage
	Significant EP Wear
	Erosion Type Fretting (Endplate Circular Impression)
Sheath Condition	White Oxide-Like Finish
	BHAZ Oxide
	Swelling
	Sheath Depression
	Ridging
	Semi-circular Indication
	Pilgering Marks
	Sheath Mech Damage

Component	Observation
End Cap Condition	Weld Flash
	Possible Incomplete Weld
	End Cap Mechanical Damage
	Spigot Contact
	Interior Mech Damage
	End Cap Latch Marks
Bearing Pad Condition	BP Mechanical Damage
	Erosion Type Fretting (BP)
	FSW
	NFSW
	Abnormal Wear
	Sculpted Wear
Spacer Pad Condition	Spacer Pad Wear

Table 2 Observations of Bundle & Component Condition Trended to Monitor Fuel Performance

Anomalies are identified by expert review of irradiated fuel inspection results. The experts are able to identify rare or previously unseen observations as well as observations that may have a significant impact on fuel performance. Once an anomaly is identified, further investigation is pursued, just as with changes in trends.

Operating envelop fuel performance is analyzed by considering the inspection results from the bundles that were inspected under the Compliance inspections task. The high burnup and high power inspections are analyzed to determine if there was any abnormal oxide growth on sheath surfaces. Elements from these bundles are also occasionally included in PIE shipments to allow for the assessment of pellet condition. The cross flow inspections are analyzed to determine if there was any excessive wear attributed to vibration of the fuel bundle.

Defect fuel performance is analyzed by considering the inspections results from the bundles confirmed to be defective. The goal of this analysis is to identify the cause of the defect and recommend actions to prevent re-occurrence of that type of defect. To ensure that all defects are analyzed, the unit radiochemistry data is also considered to determine if there was failed fuel in the core that could not be located.

The analysis objectives for the bundles flagged for inspection under the specific operational, manufacturing or design related tasks are specific to those tasks. For example, the primary concern for the tasks related to acoustics is to determine if the are any endplate cracks and the character of all observed cracks. The analysis objectives for these tasks are identified when the tasks are first created to guide both the inspectors and the analysts when they are considering these bundles.

Semi-annual inspection reports were introduced in 2012. The reports identify new trends efficiently and are a effective means to disposition fuel performance concerns.

3.3 Reporting Results

Analysis results are shared by fuel fitness for service assessment section with the fuel sub-disciplines (Fuel & Physics, Fuel Inspection & Fuel Procurement) on a continuous basis. Results are also shared with other major disciplines related to fuel (Safety Analysis, Fuel Channels & Other Interfacing Systems) primarily through the Fuel & Fuel Channel Program [10]. All of these stakeholders assist in the process to identify the apparent cause of fuel performance issues and to implement corrective actions to disposition the issues. Significant adverse conditions are reported through the Station Condition Record process [11].

Inspection results are also shared with other utilities through the COG OPEX system and observation of eachother's Fuel & Fuel Channel Program / Fuel Program meetings.

Finally, the results are also reported to the CNSC in the Annual Fuel Performance Reports in a template specified by the CNSC.

4. Conclusions

There have been significant efforts in recent years to improve the inspection planning and inspection analysis. These efforts have improved the consistency and overall quality of the fuel performance monitoring program.

Bruce Power is planning further improvements to the fuel performance monitoring program, including preparing a fuel performance monitoring program procedure, revising the inspection technical specifications and improving consistency in year-to-year inspection capacity.

5. References

[1] "Plant Reliability Integration", BP PROG 11.01, R003.

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[10] "Fuel and Fuel Channel Program", BP-PROC-00893, R000, December 10, 2012.

[11] "Station Condition Record Process", BP-PROC-00060, R024, March 11, 2013.