OPG Fuel Surveillance Program

by

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ABSTRACT

The Ontario Power Generation (OPG) fuel surveillance program was initiated in response to a Canadian Nuclear Safety Commission (CNSC) Generic Action Item to verify the condition of CANDU® fuel irradiated in Canadian reactors. As part of a comprehensive response, OPG committed to performing in-bay fuel inspection and hot-cell examinations. Based on the in-bay inspection results, a selection of fuel was shipped from each reactor site to Chalk River Laboratories (CRL) for post-irradiation examination (PIE).

Typically, 15 loose elements (from a variety of fuel bundles) or a single bundle are sent to CRL. The PIE is intended to

- Provide data for assessment of fuel performance,
- Check compliance of operating fuel with design and operating limits,
- Determine the defect root cause for failed fuel elements,
- Provide data to characterize the actual condition of fuel during operations, for use in licensing analyses, and
- Provide longer-term assurance that measurable fuel operating parameters are not deviating from the established norms.

Since 1999, a total of 103 individual fuel elements from 40 fuel bundles and two intact fuel bundles have been sent to CRL for PIE. The examinations are used to monitor several fuel performance parameters (i.e., fission gas release, grain growth, and residual sheath strains). Fuel performance has been good and representative of what has been previously observed. A total of 9 defected fuel elements from 9 fuel bundles have been examined. The majority of these fuel bundles (7) failed as a result of debris fretting. The fuel bundle defect rate at OPG remains well below 0.01 percent for the last five years. Details of the PIE results are presented in this paper.

INTRODUCTION

The Ontario Power Generation (OPG) Fuel and Fuel Channel Program established a comprehensive monitoring program as part of its commitment to the CNSC in support of the Generic Action Item on fuel condition “GAI-94G02”. A detailed strategy for fulfilling this commitment was developed and implemented in 2000. The program involves in-bay and hot-cell inspections of irradiated fuel from each of its operating stations (Darlington and Pickering A and B).

The in-bay inspection documents the mechanical integrity of the fuel bundle and is used as part of the fuel selection process for post-irradiation examination (PIE) in the hot-cells. The PIE in the hot-cells is intended to

- Provide data for assessment of fuel performance,
- Check compliance of operating fuel with design and operating limits,
- Determine the defect root cause for failed fuel elements,
- Provide data to characterize the actual condition of fuel during operations, for use in licensing analyses, and
- Provide longer-term assurance that measurable fuel operating parameters are not deviating from the established norms.

Another component of the monitoring program is to perform engineering tests on irradiated and un-irradiated fuel bundles.

On-site inspections in the irradiated fuel bays (IFB) are the most convenient and inexpensive inspections available to OPG, and provide a wealth of data regarding fuel performance and behavior. These IFB inspections are effective in resolving many fuel performance and design issues (e.g., the extent of bearing pad wear). However, certain important measurements and investigations are not possible using existing techniques available for IFB inspections (e.g., some defect root cause investigations, fission gas volume). These measurements must be performed in the hot-cells. The following table summarizes the various fuel performance parameters that are monitored by OPG using both in-bay and hot-cell techniques.

TABLE 1. OPG FUEL PERFORMANCE MONITORING PARAMETERS

• Power/burnup envelope • Power cycling during load following • Chemical compatibility • Bearing pad wear • Debris fretting • Sheath corrosion (deposits: crud, oxide, hematite) • Bearing pad crevice corrosion • Fission-gas release	• Power ramps during refueling • Time in air chamber of transfer mechanism • Reactor rate of power rise • Outer element bowing and inter-element spacing • Maximum fuel temperature • Fuel recycling • Average diametral strain at the pellet mid-plane

Since 1999, a total of 103 individual fuel elements from 40 fuel bundles and two intact fuel bundles from Darlington and Pickering Nuclear Generating Stations (DNGS and PNGS) have been sent to CRL for PIE as part of the OPG fuel surveillance program. The DNGS fuel consisted of standard and long fuel bundles . The typical fuel surveillance PIE program consists of visual examinations, bundle and element mensuration, gas puncture and gas composition analysis, metallographic and ceramographic examination, and specialty examinations (burnup, scanning electron microscope, defect root cause determination). The highlights of the PIE of this fuel will be described in the following sections.

RESIDUAL SHEATH STRAIN AT THE PELLET MID-PLANE LOCATION

Typically all intact elements shipped to CRL are measured to ± 0.01 mm, using a dual-transducer profilometer. The element diameter is measured at three orientations: 0°, 120°, and 240°. Diameter measurements from the three orientations are averaged and subsequently the diameters at the mid-pellet (MP) locations are determined. The percent residual sheath strain at the MP locations is calculated as follows:

$$\%\ \text{Residual Sheath Strain} = 100 \times \frac{\left(d_p - d_i\right)}{d_i}$$

Where d_p is the average post-irradiation MP element outside diameter (OD) and d_i is typically the manufacturer nominal OD. The average residual sheath strains at the element MP for DNGS and PNGS fuel ranged from compressive to tensile strain (-0.4% to 0.2% and –0.1% to 0.3%, respectively). The residual sheath strain at the mid-pellet increases with burnup and maximum element power as shown in Figures 1 and 2. The DNGS and PNGS MP residual sheath strain results do not exceed the 0.5% internal OPG threshold and are comparable to those previously reported [(1)].

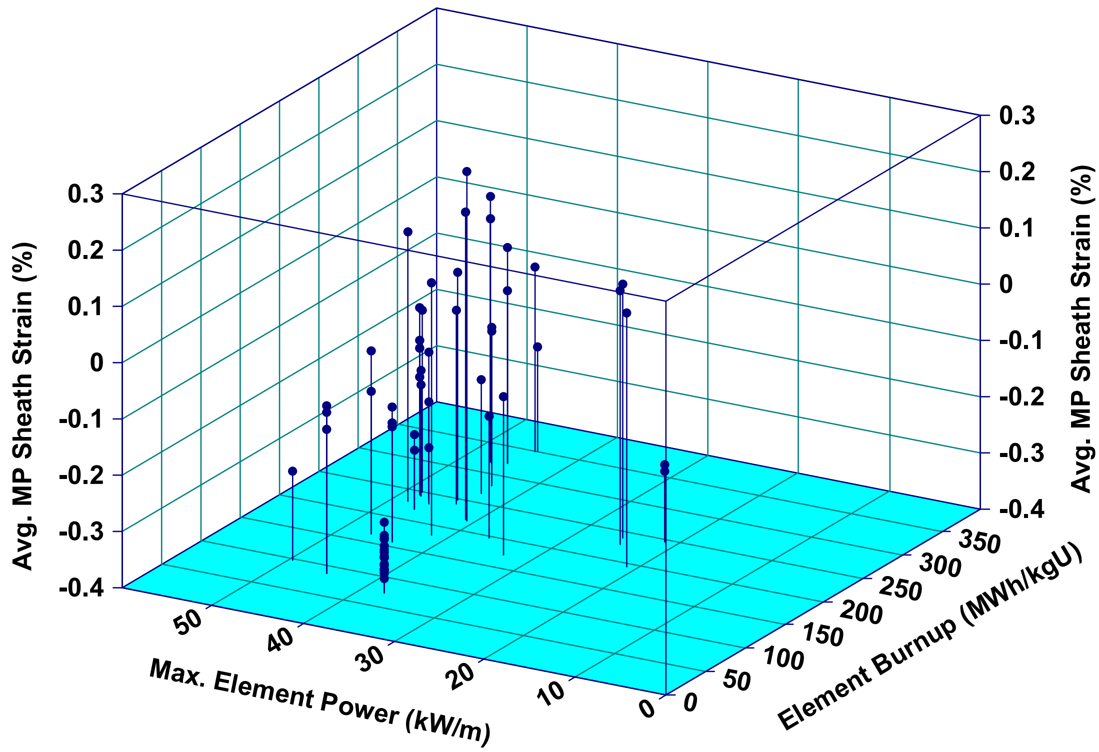


FIGURE 1. DNGS FUEL ELEMENT MP RESIDUAL SHEATH STRAIN

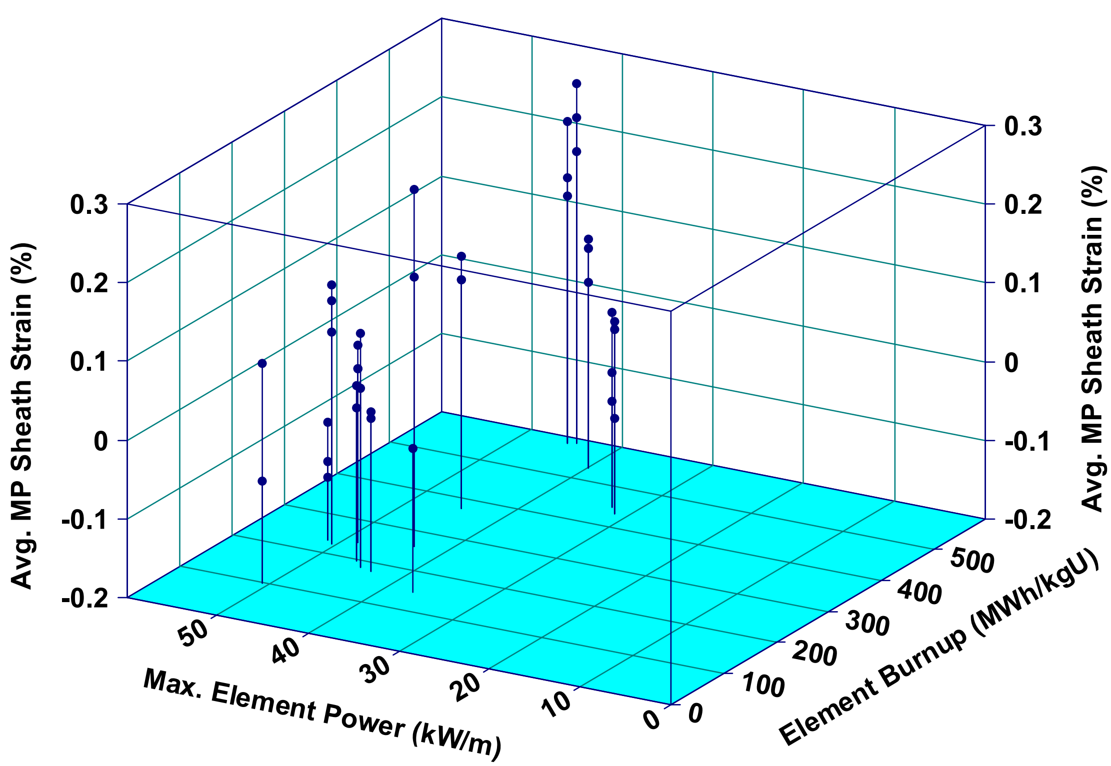


FIGURE 2. PNGS FUEL ELEMENT MP RESIDUAL SHEATH STRAIN

GAS VOLUME AND FISSION GAS RELEASE

The majority of the intact fuel elements are punctured to determine the end-of-life (EOL) free gas volume within the element. The gas volume for normally operated DNGS and PNGS fuel (i.e., <350 MWh/kgU discharge burnup) ranged from 2 to 16 mL, which is well below OPG's threshold. Some of the elements also had their gas composition determined using a gas mass spectrometer to determined the Xe and Kr fission gas release.

In addition, PNGS fuel elements that resided in a fuel channel for an extended period because of fueling restrictions were sent to CRL. This fuel operated to bundle average burnups ranging from 385 to 552 MWh/kgU. The lower power bundles had gas volumes that ranged from 2 to 4 mL compared to the higher power bundles whose gas volumes ranged from 20 to 55 mL. The PNGS bundle that operated to the highest burnup (well above normal discharge burnup due to fueling restrictions) exceeded the 40 mL OPG threshold. However, PIE confirmed that the elements were intact.

The gas volume data as a function of maximum power and element burnup is shown in Figure 3.

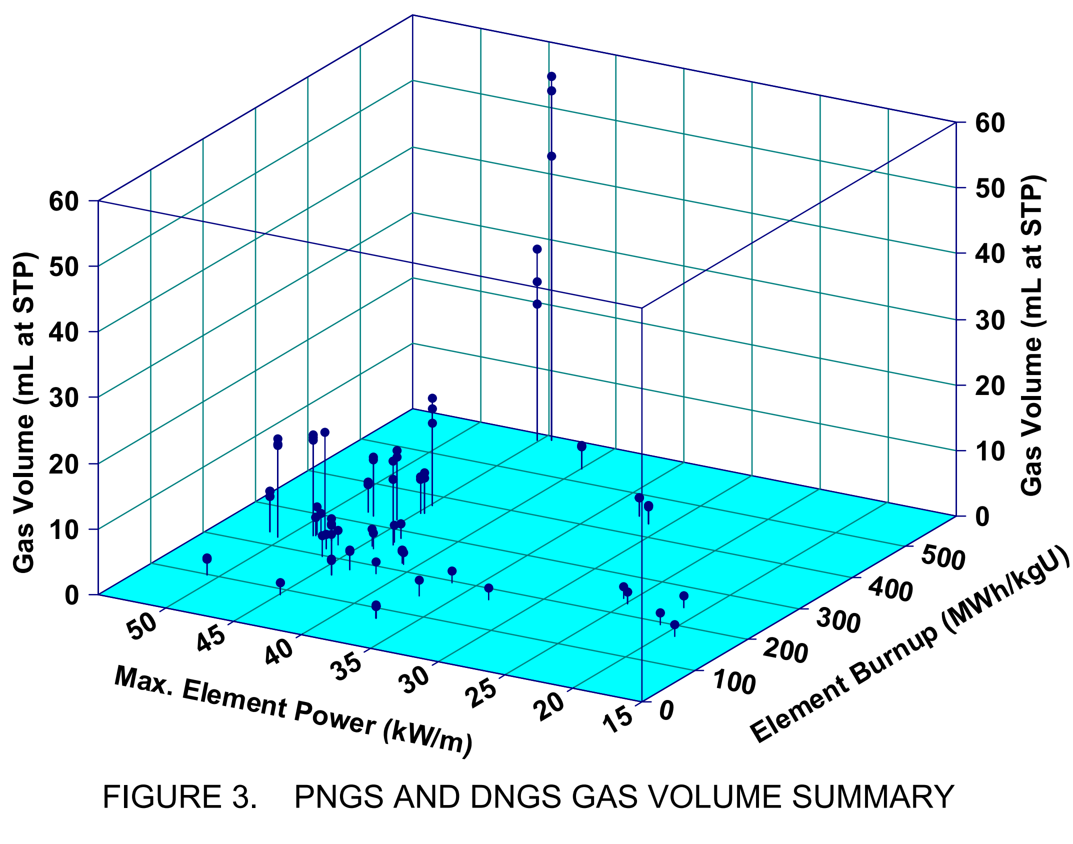


FIGURE 3. PNGS AND DNGS GAS VOLUME SUMMARY

The plot shows that the element gas volume remains low until the element power exceeds about 45 kW/m. Increase in EOL gas volume is directly related to the increase in fission gas release (i.e., <0.1% to 7% FGR) (see Figure 4).

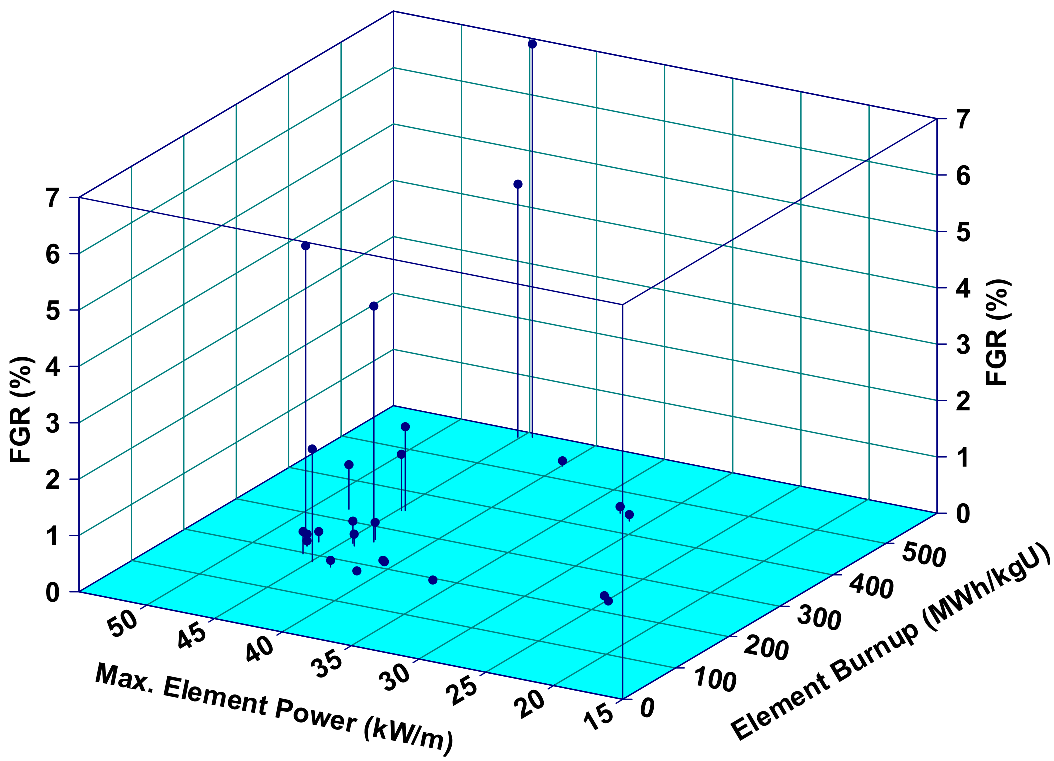


FIGURE 4. PNGS AND DNGS FGR SUMMARY

The FGR is the percentage of Xe and Kr released from the total Xe and Kr produced in the UO_2 matrix into the element free void. OPG does not have an FGR compliance limit but the measured FGR for these recent examinations are comparable to other fuel operated at similar conditions [(1)]. Similarly, the measured internal fission gas volumes are consistent with historical measurements.

FUEL SHEATH HYDROGEN AND DEUTERIUM PICKUP

Past studies have shown that hydrogen and deuterium ingress into the fuel sheath is not a direct threat to CANDU fuel performance; however, it may influence fuel performance (e.g., stress-corrosion cracking thresholds) [(2), (3)]. As a result, sheath hydrogen and deuterium content is routinely monitored. The hydrogen and deuterium content was measured for fuel sheath samples taken from the heat-affected zone (HAZ; i.e., bearing pad region) and from the as-received zone (ARZ; i.e., midway between the bearing pad locations) using a hot-vacuum extraction mass spectrometry technique.

The fabrication specification for sheath hydrogen concentration is 25 μg/g (maximum). Typically, most fuel sheaths received from the manufacturer have a nominal concentration of about 15 μg/g. During irradiation, additional hydrogen ingress comes from the element internals such as the CANLUB coating and pellets. The sheath hydrogen concentration from the latest measurement of PNGS and DNGS fuel elements ranged from 12 to 32 μg/g, which is well within the range of historical results of

10 to 80 μg/g. The average hydrogen concentration at the ARZ and HAZ was comparable (i.e., 18±3 versus 21±4 μg/g, respectively). There is no correlation of hydrogen ingress (ARZ and HAZ) with burnup or irradiation time as illustrated in Figure 5.

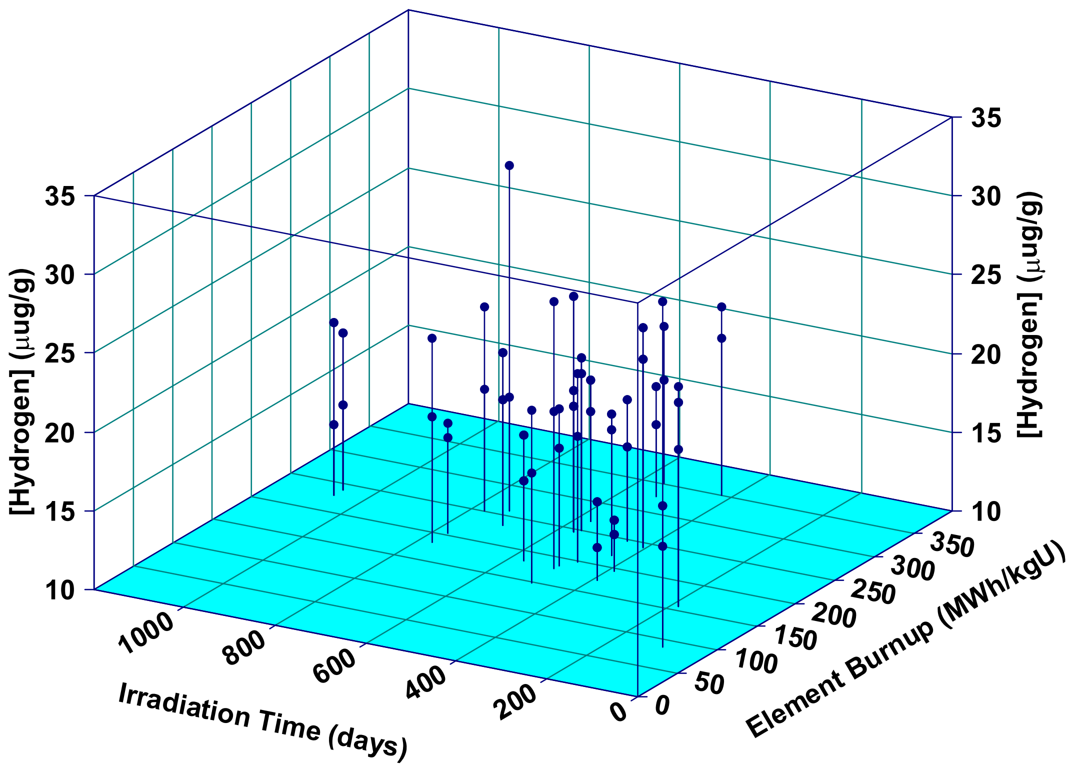


FIGURE 5. SHEATH HYDROGEN CONCENTRATION VERSUS BURNUP

The historical deuterium sheath concentration results (ARZ and HAZ) contain a significant amount of scatter as shown in Figure 6; however, the data indicates that the deuterium ingress increases with burnup and irradiation time to some degree. The current data shown in Figure 7 is not as scattered as the historical data but also shows the same trend.

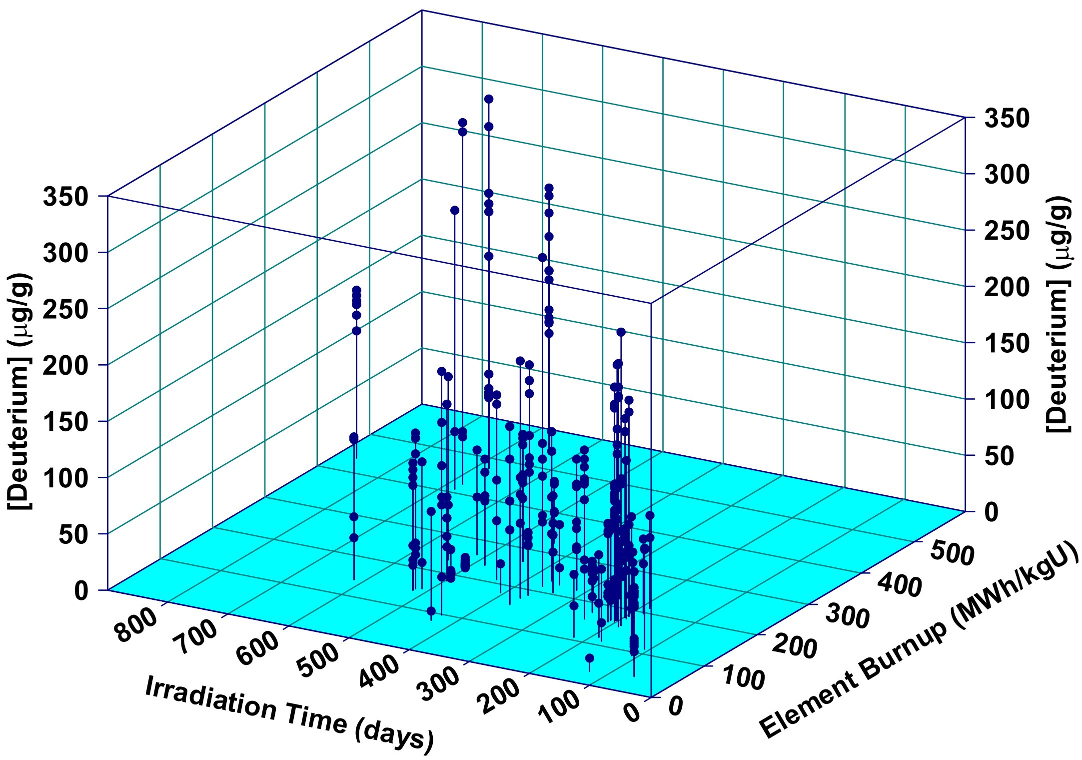


FIGURE 6. HISTORICAL SHEATH DEUTERIUM CONCENTRATION (ARZ AND HAZ) AS A FUNCTION OF BURNUP AND IRRADIATION TIME

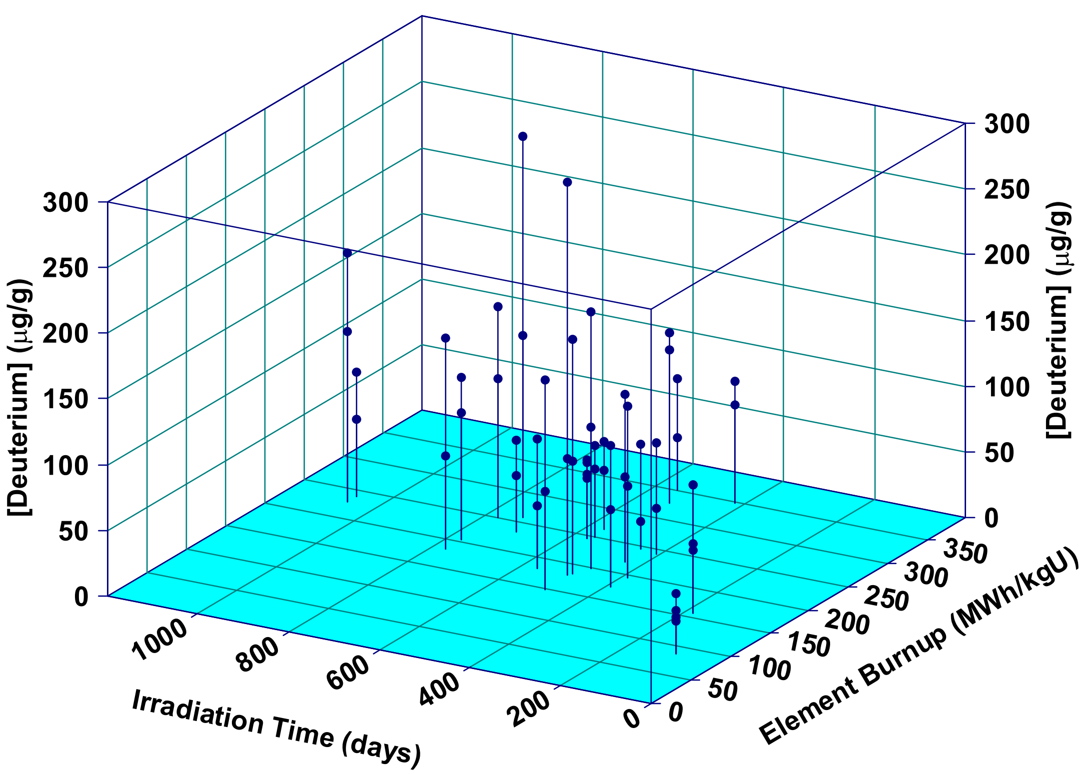


FIGURE 7. RECENT SHEATH DEUTERIUM CONCENTRATION (ARZ AND HAZ) AS A FUNCTION OF BURNUP AND IRRADIATION TIME

The deuterium content in the HAZ was typically greater than the ARZ. The deuterium concentrations from the latest fuel surveillance campaign were well within the range of historical data as shown in Table 2.

TABLE 2. DEUTERIUM SUMMARY

Element Type	Deuterium Range (μg/g)	
	ARZ	HAZ
PNGS (latest data)	27 to 139	124 to 300
PNGS (historical data)	17 to 214	24 to 360
DNGS (latest data)	25 to 130	58 to 190
DNGS (historical data)	2 to 189	2 to 329

COMPARISON OF MEASURED AND CALCULATED BURNUP

Bundle average burnups are calculated using the Simulation of Reactor Operation (SORO) code at OPG. Recently the burnup was chemically measured for a large number of DNGS and PNGS fuel samples and compared to the SORO calculated burnup.

Fuel chemical burnup measurements were determined by measuring the concentration of a fission monitor. For CANDU fuel, the stable fission monitor ^{139}La is used for the burnup determinations and is measured using high performance liquid chromatography [(4)]. The ^{139}La concentration is then converted to a burnup value (i.e., MWh/kgU) using a physics code. The chemically measured burnups were in good agreement with SORO calculated burnups (i.e., within ±3% of the calculated burnup) as seen in Figure 8.

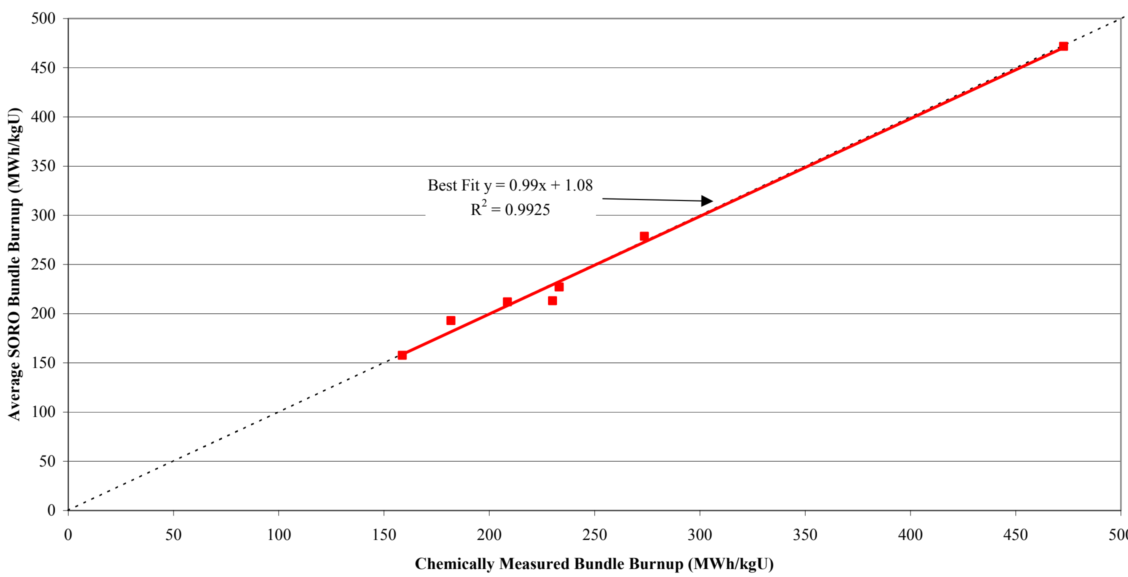
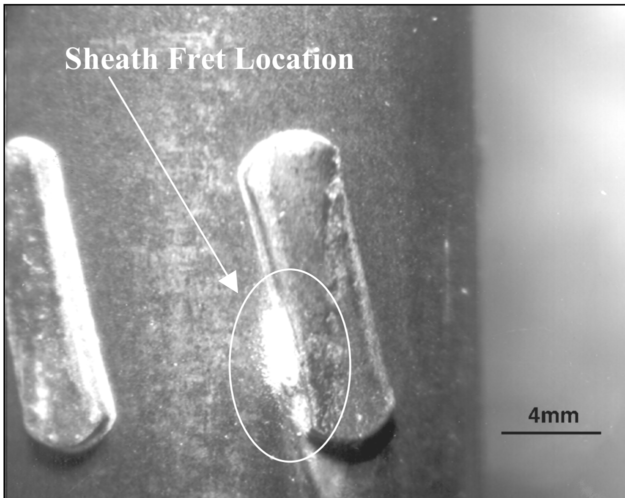


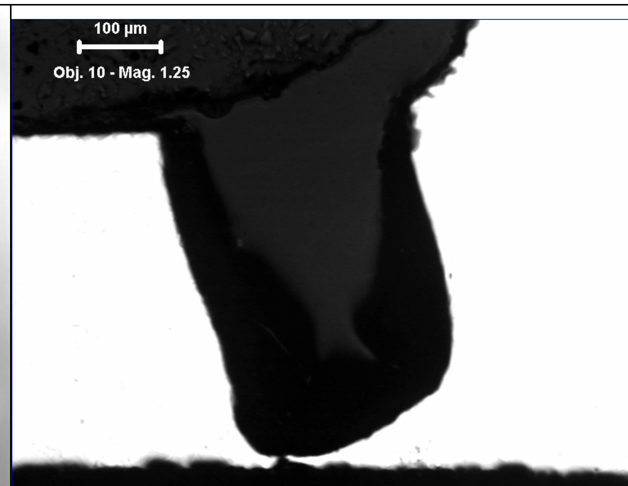
FIGURE 8. SORO PREDICTED BUNDLE-AVERAGE BURNUP VERSUS CHEMICALLY MEASURED BUNDLE BURNUP

DEFECT ROOT CAUSE DETERMINATION

Nine defected elements from 9 different bundles (5 PNGS and 4 DNGS bundles) were shipped to CRL for defect root cause determination. Two of the five PNGS defects were the result of debris fretting (see Figure 9).



Debris Fret



Metallographic Cross Section of the Fretted Sheath

FIGURE 9. PNGS ELEMENT THAT FAILED AS A RESULT OF DEBRIS FRETTING

The remaining three defected PNGS elements experienced significant secondary damage and it was not possible to determine the primary defect root cause. Detailed examinations of the closure weld (i.e., end-cap to sheath welds) did not reveal any manufacturing defects.

Two DNGS fuel bundle defects were the result of debris fretting. The other failures were the result of an incomplete closure weld as shown in Figure 10.

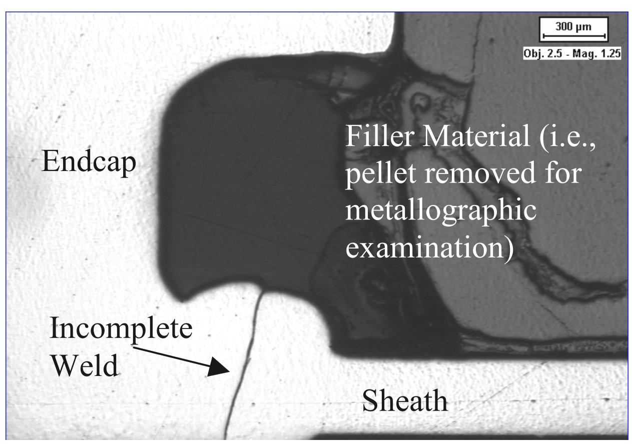


FIGURE 10. DNGS ELEMENT THAT FAILED BECAUSE OF AN INCOMPLETE CLOSURE WELD

The fuel bundle defect rate at OPG has been well below 0.01 percent for the last five years.

CONCLUSIONS

Overall, OPG's in-bay and hot-cell PIE program has addressed the CNSC Generic Action Item on fuel condition "GAI-94G02". The PIE has shown that fuel performance is good and is comparable to previous observations and to that predicted by fuel performance codes.

A byproduct of the OPG hot-cell PIE program is that it provides researchers with a large variety of fuel that can be used in other research programs (e.g., oxygen-to-metal determination, fission product migration, etc.) [5], [6]. OPG has been generous in sharing the results of its PIE program with industry research initiatives.

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