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FUEL DEFECT DETECTION AND LOCATION METHODS AT PICKERING NUCLEAR GENERATING STATION

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ABSTRACT – Pickering Nuclear Generating Station (PNGS) fuel performance has been described as good [1] and the station is actively working to achieve the industry target of 'zero' fuel defects [2]. PNGS is not equipped with fuel defect locating instrumentation, such as commissioned gaseous fission product detectors, delayed neutron systems or feeder scanners. To identify the presence of a fuel defect, its location, and confirm its discharge, PNGS uses alternate methods such as: bulk Heat Transport System (HTS) iodine and xenon grab sampling, individual HTS loop sampling, and gamma and airborne iodine monitoring during fuel discharge.

Introduction

Pickering Nuclear Generating Station (PNGS) has experienced few fuel defects in the past five years, with a residence time in-core of six months or more. PNGS is endeavouring to decrease that residence time, despite not having gaseous fission product detectors, delayed neutron systems or feeder scanners. Due to the lack of advanced fuel defect locating equipment, fuelling engineers are limited to classic methods of defect detection and location. The methods currently in use are: Heat Transport System (HTS) grab sampling and analysis of fission product isotopes, individual HTS loop sampling with the intent of halving the core, and gamma monitoring of discharged fuel, with future online airborne I-131 monitoring during fuel discharge.

1. General fuelling facts

PNGS units 1-4 have 390 fuel channels, while units 5-8 have 380 fuel channels. Each channel houses 12 fuel bundles comprised of 28 elements, resulting in 772,800 fuel elements in all of Pickering that have the potential for a fuel defect. The number of bundles fuelled per year is approximately 17,000 and the average in-core residency for a bundle is ~365 days.

PNGS reactors are fuelled using a 4/8 fuel shifting scheme. Centre core fuel channels are fuelled with four fresh bundles approximately every four months. Outer zone (periphery) fuel channels are fuelled with eight fresh bundles at each fuelling visit. Fuelling direction is in the same direction as coolant flow.

2. HTS grab sampling

The traditional method of defect monitoring at nuclear power stations is HTS grab sampling and analysis. At PNGS, each unit's HTS is sampled two times weekly if there is no defect, and every twelve hours if a defect is present. Additional sampling requirements are communicated by fuelling engineers through a special note on regular Fuel Change Orders. Grab samples are analyzed by a gamma spectrometer, whose output is a paper printout. A chemistry technician then manually enters the relevant values into the station chemistry database. Until 2015, only I-131 and I-134 were reported in the database for defect monitoring purposes, as they are required for the calculation of the WANO Fuel Reliability Index. In 2015, with multiple fuel defects at PNGS, there was a need to diagnose and locate defects more efficiently. Analysis of additional fission products was initiated as a way to improve defect monitoring capability.

I-131 is used as the primary indicator of whether a fuel defect is present in core at any time. The half-life is eight days, but holdup of soluble I-131 in the fuel-to-sheath gap may delay release into the HTS. Additionally, the high solubility means that it is continuously being removed by the HTS purification system. I-131 trending is nevertheless extremely helpful; an increase above baseline for the particular unit indicates the presence of a defect, and an I-131 spike during fuelling of a channel may indicate the location of the defect. Based on operating experience, a defect often experiences high fission product release rates shortly after moving the defect bundle from a low-power region of the core into the higher power region of the core (for example, bundle power ramp during movement from fuel in positions 1-4 to positions 5-8). A fuel defect caused by debris fretting may occur at any time, independent of fuelling.

Standard practice at PNGS, after the occurrence of an I-131 spike, involves designating all channels fuelled in the prior 5-7 days as “suspect defect channels”. The unit-responsible fuelling engineer then informs the operating organization of the presence of a fuel defect, which ensures that HTS grab sampling frequency is increased to every twelve hours. The fuelling engineer then schedules the suspect channels for fuelling as early as possible, based on:

- Severity of associated I-131 spike
- Clusters (two or more neighbouring channels identified as suspects)
- Core restrictions:
    - Sufficient time and spacing between the fuelling of neighbouring channels to avoid simultaneous power peaking due to effects of plutonium build-up
    - Channel outlet temperature limits
    - Compliance to bundle and channel power ratio limits
    - Minimize impact to normal fuelling practice and core reactivity balance

Figure 1 shows the unit 4 HTS I-131 activity, reactor power and channel fuelling between July 2015 and January 2016. The suspect defect channels were identified as the 21 channels fuelled in the six days prior to the I-131 increase seen on July 13, 2015. Channel O18 was refuelled on January 4, 2016, and was the last channel fuelled out of the 21 channels designated as suspects. When a large I-131 spike was seen after fuelling O18, the channel was scheduled for refuelling on the following day. Fuel inspections confirmed that the defect was discharged from position 10 on January 5, 2016, and was the result of debris fretting.

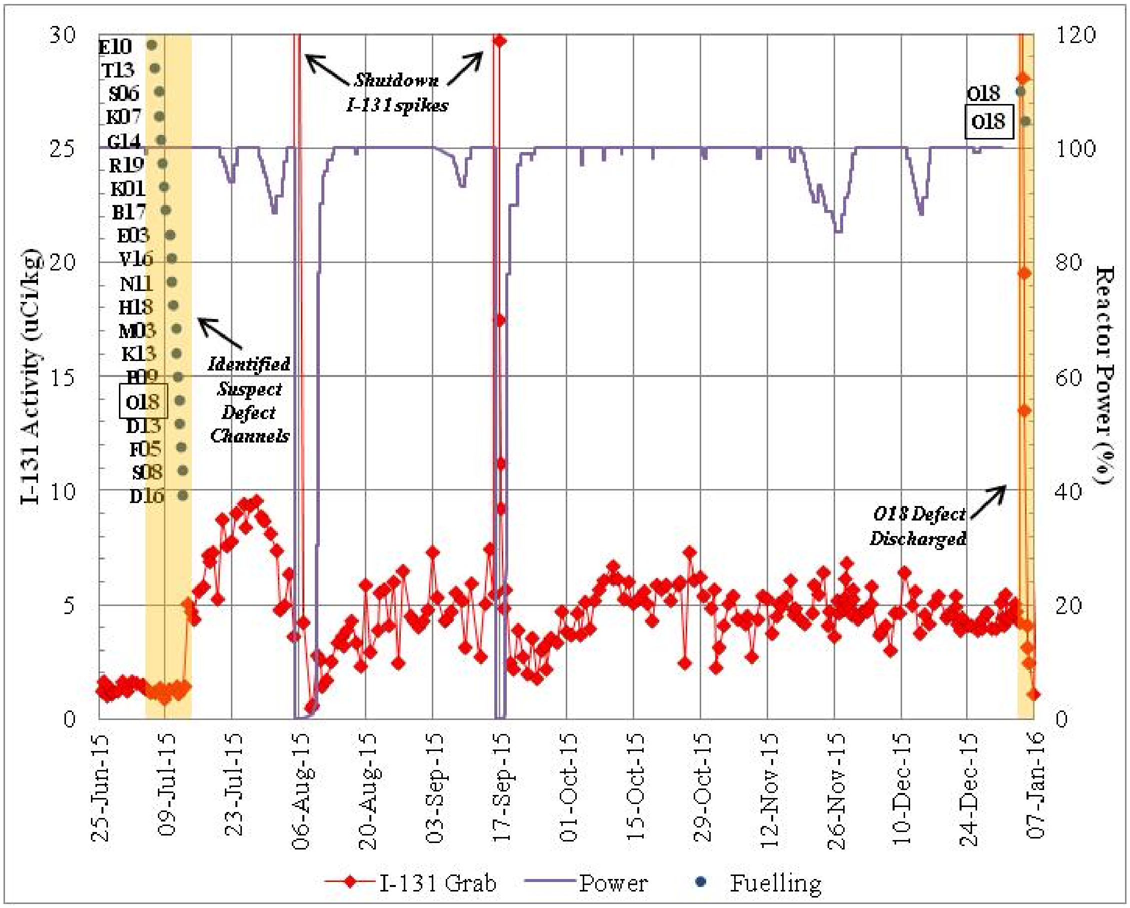

Figure 1: Unit 4 HTS I-131 activity, reactor power and channel fuelling: O18 debris fret defect was in-core from July 2015 to January 2016.

It is important to note that the fuelling-based defect removal strategy is primarily a process of elimination and that any attempt to remove a fuel defect is based on the best judgment of the limited information available.

2.1 Iodine ratios and yield-corrected release fractions

Although I-131 monitoring has always been the primary isotope used for defect monitoring in CANDUs, alternative analysis methods are being investigated at PNGS. Various sources recommend trending ratios, such as I-131/I-133, Xe-133/I-133 or Xe-133/I-131, to characterize the size of a fuel defect [3] [4]. However, in practice this ratio does not actually aid in fuel defect location, nor does it reduce defect residence time. The time-honoured I-131 grab sample was found to be just as useful at PNGS.

Similarly, the yield-corrected release rate versus the decay constant of tramp uranium (R_c/y versus λ) will clearly show the difference between a core containing defects, and a core that is defect-free [4] [5]. Where there is no defect in the core, the R_c/y versus λ plot should be a horizontal line, the height of which is proportional to the tramp uranium in the core. The downside is that multiple isotopes (I-131, I-132, I-133, I-134 and I-135) are required for this calculation, and the operator burden was considered too high to collect, verify and enter all of this information on a shiftly basis. In practice, R_c/y gives some valuable information, but is generally seen to provide the same information as the I-131 trend.

Figure 2 shows R_c/y versus λ for the periods June 2 – July 3, 2014 and July 5 – July 6, 2014. A horizontal line indicates that the fission product iodines are in equilibrium and the core is defect-free. Iodine sample data from June 2 – July 3, 2014 were averaged and plotted in Figure 2; their values form a near-flat line, indicating that the unit was defect-free at this time. The R_c/y versus λ plot for the period July 5 – July 6, 2014 forms a bent line, indicating the formation of a new fuel defect. The leftmost point is indicative of elevated I-131, and the rightmost is indicative of I-134, or tramp uranium.

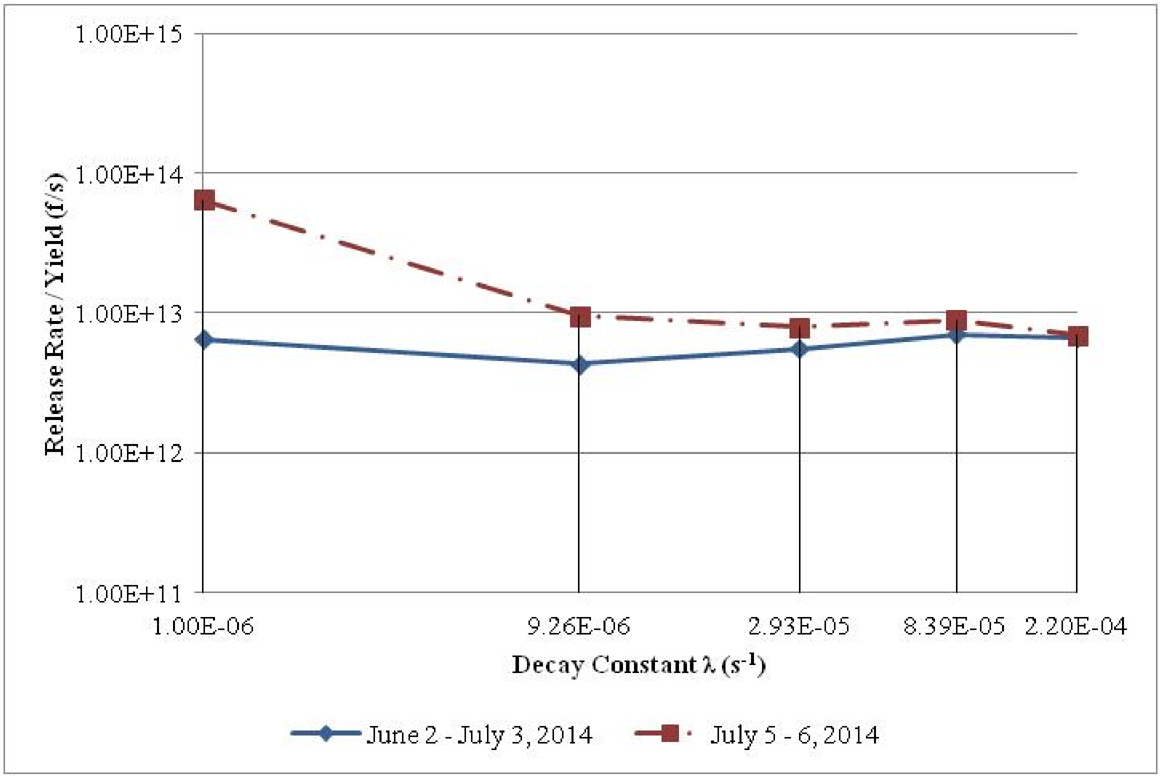

Figure 2: R_c/y plot of unit 4 iodine data, showing the transition from a defect-free core in June 2014 to the initiation of a new defect in July 2014

2.2 Xenon ratio based on PWR defect monitoring guidelines

Through research into defect detection methods at other nuclear power stations, it was found that PWRs use a calculated value called the xenon (Xe) ratio [6]. This is the ratio of long-lived Xe-133 (5.25 days) to short-lived Xe-135 (9.09 hours), and measures increase or decrease in defect activity. A defect-free core will likely have a steady state Xe ratio of less than or equal to 1.0. A gradual or sharp increase indicates the initiation of a fuel defect, and similar to I-131, a Xe ratio spike during fuelling of a channel may indicate the location of a defect. If a fuel defect is moved to a higher power region of the core, the increase in power increases the xenon output rate and the Xe ratio will tend to increase. Conversely, when the defect is moved to a lower power region of the core, the Xe ratio may spike, but will tend to decrease over time, due to the lower power output of the fuel bundle. Upon startup after a long unit outage, the Xe ratio will build to an equilibrium level from zero, the magnitude of which will depend on whether or not a defect is present in core.

Due to their gaseous nature, xenon concentrations cannot be accurately measured by HTS grab samples; they will only show general trends. However, one advantage of using grab-sampled xenons is that they have limited solubility in water and therefore are not removed by HTS purification. There is also little holdup in the fuel-to-sheath gap, and theoretically a xenon spike may be observed earlier than an iodine spike. Due to the lack of online gaseous fission product monitoring capability, xenon and iodine samples are taken concurrently according to the Chemistry lab schedule, and to date, no advance xenon spikes have been seen at PNGS.

The Xe ratio for unit 1 from December 2013 to June 2016 is plotted below in Figure 3. The sudden Xe ratio decrease in December 2014 indicates that a defect was either discharged or moved to a much lower power level prior to the unit outage in January 2015. Upon unit restart, between January 31 and April 29, 2015, the continued presence of a fuel defect is confirmed with an equilibrium Xe ratio of ~2.0. Upon unit restart in late August 2015, the Xe ratio stabilized at ~1.0, and I-131 activity was low, therefore the unit was declared defect-free.

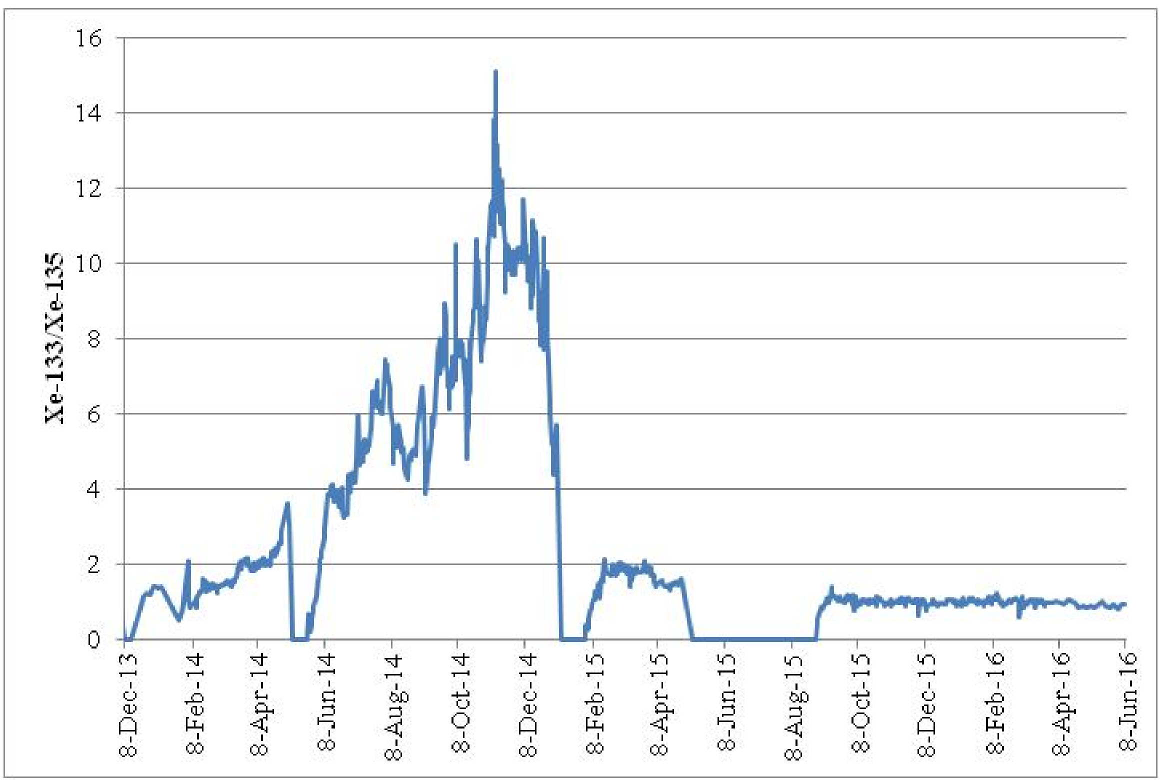

Figure 3: Unit 1 HTS Xe ratio from December 2013 to June 2016. Xe ratio greater than 1.0 indicates the presence of a defect in unit 1 [7].

Furthermore, using the known decay rates of both Xe-133 and Xe-135, an idealized Xe ratio decay curve can be superimposed over the actual Xe ratio curve to determine whether or not the defect has been discharged. When a defect is discharged, the Xe ratio will trend towards steady-state value, which is usually approximately 1.0. If it has been moved to a higher or lower power region of the core instead, the Xe ratio will be trending towards either a higher or lower value than previously, but will remain greater than 1.0. The behaviour of the Xe ratio after fuelling a suspect defect channel will give valuable information on whether that defect remains in core, and in which fuelling position it likely resides.

Figure 4 shows how the idealized Xe ratio decay curve was superimposed over real data [7]. This ideal curve was superimposed onto each fuelling run leading to an I-131 spike in late 2014 and early 2015. It was found that the fuelling run which matched the closest to the ideal was that of suspect defect channels N17 and S10, fuelled on December 23, 2014. These bundles will be inspected after the CANDU Defect Fuel Bundle Loading/Unloading Platform is installed at PNGS in mid-2016 [8].

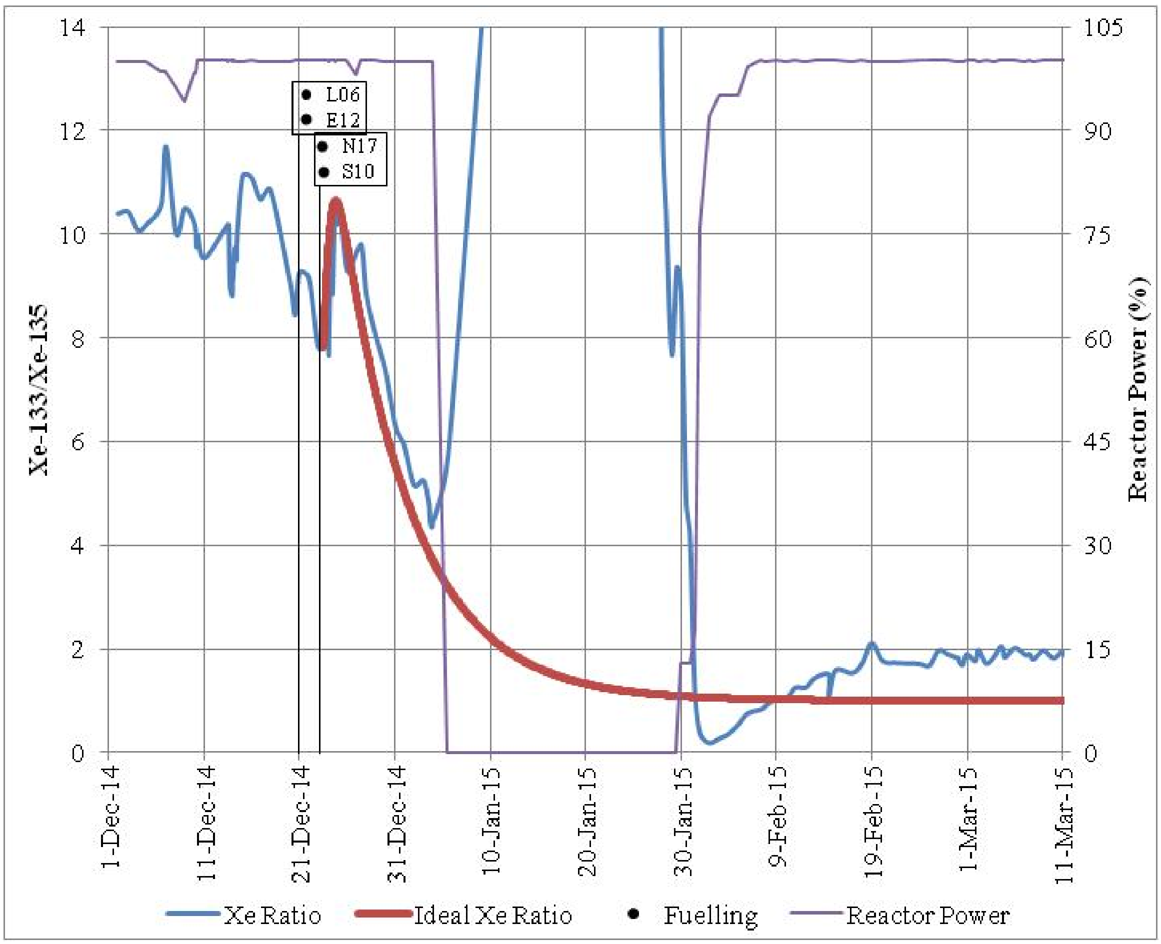

Figure 4: Superimposed idealized Xe ratio decay curve over actual Xe ratio from December 2014 to March 2015. N17 and S10 considered most likely to be defects [7].

3. Individual HTS loop sampling on units 5-8

Another defect location method that may decrease defect residence time in core is individual HTS loop sampling. The HTS is divided into two loops, North and South, and although they intermix to some degree, the loop containing the defect will tend to have higher a concentration of fission products.

In PNGS units 5-8, sample points for each North and South loop are available on power for most units. Iodines or Xe ratios from each loop can be compared directly and the list of suspect defects can essentially be halved, as the suspect list will be confined to those suspect defect channels that reside in the HTS loop with the higher fission product inventory.

PNGS unit 8 contained a fuel defect from February to July 2015, but only had the North and common system sample points available at power. Due to unit conditions and testing requirements independent of the fuel defect management campaign, the balance between North and South flow ("bias") was being varied by Operators, while HTS grab samples were being obtained from both the North loop and the common sample points, shown in Figure 5.

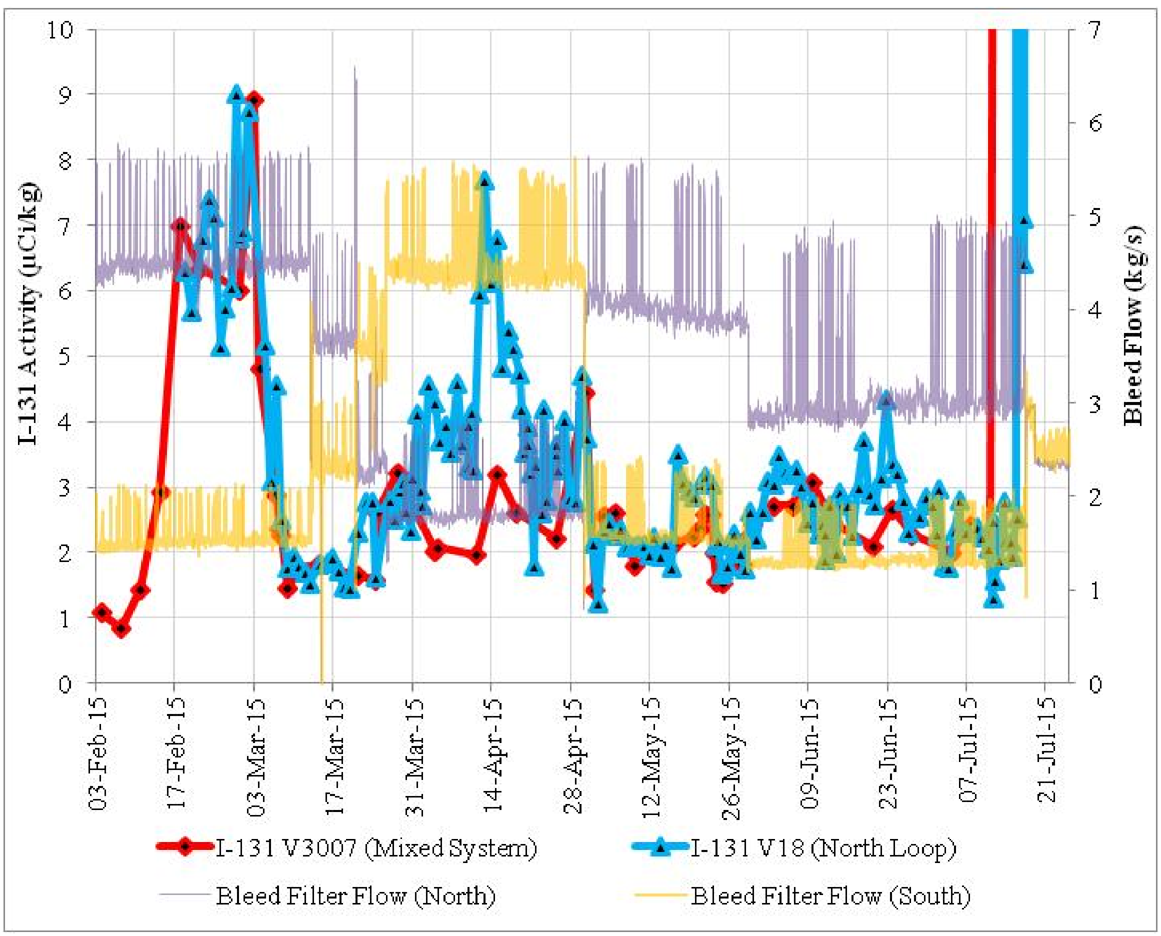

Figure 5: Unit 8 HTS I-131 activity and purification loop bleed flows. Defect bundle was residing in the North Loop [9].

When system sample results and North loop activity were compared against the biased purification system bleed flows (see Figure 5), the following observations were noted:

a) When the North loop bleed flow was greater than the South, North loop I-131 activity typically converged with system activity.

b) When South loop bleed flow was greater, North loop I-131 activity typically increased, diverging at times significantly from system activity.

Fuelling engineers were able to observe how I-131 levels would vary with flow configuration, and determined that the defect resided in the North loop. The suspect defect list was then reduced to only North channels, and the defect was discharged from the North loop in July 2015 [9].

3.1 Simulation of individual HTS loop sampling on units 1 and 4

PNGS units 1 and 4 do not have North or South sample points available at power. These were removed or capped for legacy reasons. Consequently, two methods of simulating North/South loop separation are currently being pursued.

The first method involves the unit Operator manually varying the flow bias, and obtaining HTS grab samples as the flow is first biased to the North loop, and then to the South loop. This approach will be used in the event of a future defect.

The second method is to be performed while fuelling is in progress, as it has been observed that while fuelling is in progress, coolant flow increases in the loop being fuelled. Therefore, it is thought that an HTS grab sample obtained at this time may be more representative of that loop than the other one. If a grab sample is then obtained during fuelling of a channel in the other loop, the values may be compared. This procedure was implemented in mid-2016. As the units were defect-free at the time, no difference was seen and the results of the procedure will be used as a baseline in the future.

4. Gamma and I-131 monitoring in fuel transfer rooms

Gamma monitoring of fuel upon discharge has been used successfully on PNGS units 5-8 to identify or confirm a fuel defect as it is being discharged from the core. Irradiated fuel is discharged from the reactor to the fuelling machine (FM) to the transfer mechanism (TM). Fuel is kept underwater during this transfer, and then the TM is partially drained to prepare for transfer of irradiated fuel to the fuel elevator. This water is drained into a tank in a separate room, which contains a fixed area gamma monitor (FAGM). If the fuel in the TM is defected, a radiation alarm would be observed from the main control room, and the fuel would then be set aside for inspection. Figure 6 shows a typical FAGM reading upon discharge of a defect from unit 6 in 2009.

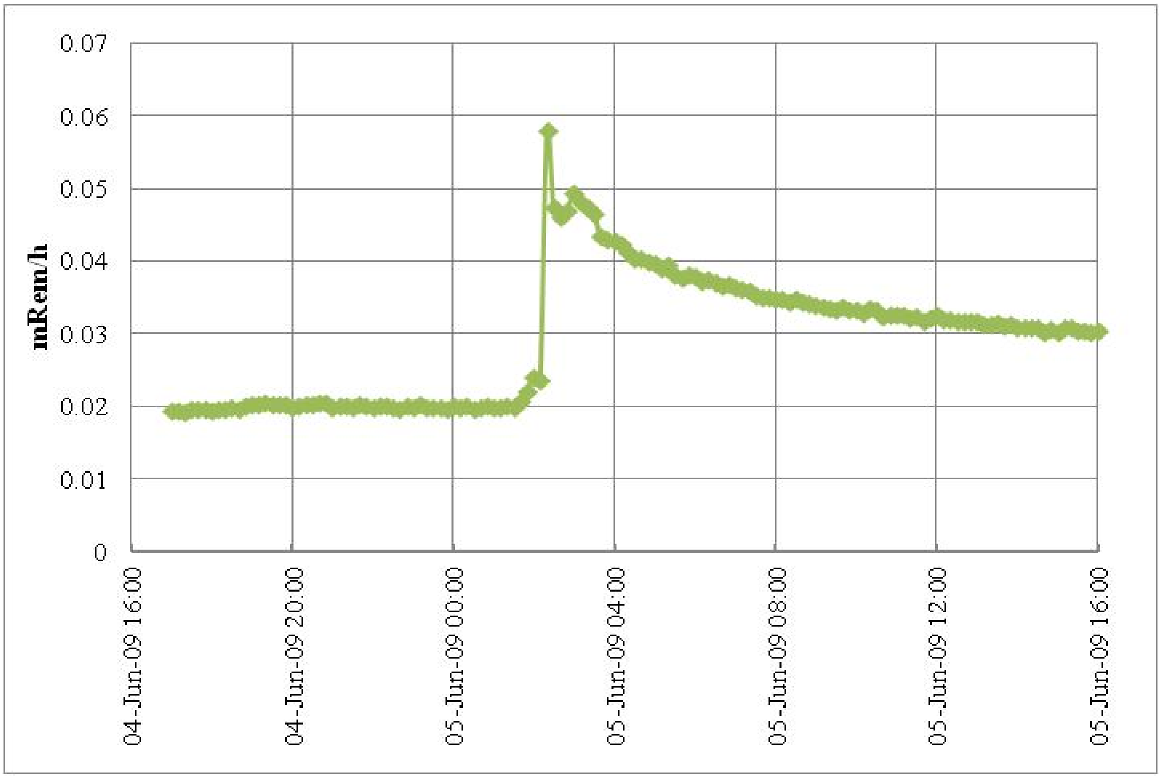

Figure 6: Gamma monitoring of defect fuel discharged from unit 6 in June 2009.

Due to differences in FH equipment configuration on PNGS units 1 and 4, a similar FAGM system is not possible. A portable area gamma monitor (PAGM) was thus installed in both units 1 and 4, near the tank that drains water from the FM instead. These PAGMs on the FM water tank were not able to discern between gamma radiation from defect fuel and that from other sources.

Whenever the fuelling engineer identifies that a suspect defect channel is being fuelled, manual gamma surveys, as well as airborne I-131 and particulate sampling, are done before and after fuelling, by qualified FH personnel. This method of defect monitoring is highly dependent on sample timing, and the exact level of expected readings is not well understood, due to the infrequency of samples and high measurement variability. To improve the survey results, PNGS has procured portable airborne I-131 monitoring equipment for placement in the FH accessible area of unit 1 or 4, to provide continuous sample results that would be wirelessly transmitted to the station Graphical Electronic Dosimetry Display System (GEDDS).

5. Conclusions

Due to the lack of advanced fuel defect monitoring equipment at PNGS, fuelling engineers are looking to alternative methods of fuel defect detection and location. Iodine and xenon grab sampling, as well as iodine and xenon ratios are being analysed, analysis of the individual HTS loops is performed on units 5-8 and is being simulated on units 1 and 4, and gamma and airborne I-131 monitoring equipment is used to confirm the final discharge of defect fuel. Fuelling engineers are continuing to work on improving defect detection and location methods as the station works towards the industry goal of zero fuel defects.

6. References

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