Using On-Line Monitoring Of Fission Products Data To Manage Reactor Operations With In-Core Failed Fuel Element(S)

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ABSTRACT

Increases in iodine activity in the Primary Heat Transport System (PHTS) coolant as a result of fuel sheath failures can threaten Unit operation if the iodine coolant activity limit in the Primary Heat Transport System (PHTS) is approached. However, shutting down the reactor increases significantly the difficulty associated with localizing failed fuel bundles. Additionally, such an action poses significant economic implication. As a result, it is important to develop methodologies that can be used to proactively manage coolant iodine concentration under different operating conditions (including startup after an outage with suspected failed fuel in the Unit) while localization efforts continues.

1.0 INTRODUCTION AND BACKGROUND

When a fuel failure occurs, ^{131}I and other fission products are released into the PHTS coolant from the fuel-to-sheath gap of the failed fuel. This release from a failed fuel element continues until the fuel is located and removed from the Unit or until the element is moved to a low-flux channel position. All Bruce Units are equipped with capabilities to monitor fission products in the PHTS, detect the presence of failed fuel bundles and localize them for removal. For the purpose of detecting and monitoring fission products evolution in the PHTS, online data collection and analysis (using the Gaseous Fission Product system, GFP) and manual grab sampling are the two methods that are used at the Bruce site. Analysis of signals from the Delayed Neutron (DN) monitoring system is the primary tool used for localizing failed fuel bundles once they have been detected.

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There are operational limits on the level of iodine concentration permitted in the PHTS. Such limits are primarily determined by potential doses to the public as a result of postulated accidents involving PHTS coolant leakage outside of the reactor containment. Whenever a fuel failure is suspected in a Unit, the primary objective is to remove it expeditiously. Until this is accomplished, the Unit has to operate with the failed fuel for a time period.

This paper presents methodologies for using on-line fission products monitoring data for proactively managing reactor Unit operation whenever failed fuel elements are suspected in the Unit. Using recently developed tools and techniques we can characterize as a function of time the evolution of PHTS fission product concentrations following an occurrence of fuel sheath failure (under steady state situation and during iodine transient). Such characterization can provide an indication of the time window available to discharge a failed fuel bundle before the iodine limit is reached or how much the Unit power could be derated to allow for unlimited time for the localization of the channel containing the failed fuel element.

2.0 FAILED FUEL DETECTION AND LOCALIZATION

Bruce Units have two automated systems for the detection and localization of failed fuel bundles. The Gaseous Fission Product (GFP) system performs the detection function and the Delayed Neutron Monitoring (DN) system is used primarily for failed fuel localization. In addition, depressurized water samples (Grab Sampling) are taken regularly to determine a “snap-shot” measurement of radionuclide concentrations in the PHTS.

2.1 Detection Capabilities

2.1.1 Gaseous Fission Product System

The GFP system continuously monitors key radionuclides in the PHTS by performing gamma spectrometric measurements on sample lines from the reactor header. These key radionuclides (^{88}Kr, ^{133}Xe, ^{135}Xe and ^{131}I) were selected as the most significant indicators of the presence of failed fuel in the PHTS.

Coolant activity measurements are continuously taken at equal collection periods of time. For each collection period, the calculated concentrations[2] of the selected isotopes are stored in the Plant Information (PI) database if their values are higher than a pre-set threshold. Additionally, summary spectra files are continuously produced for storage on

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[2] Concentration is calculated as total activity for each fission products in the PHTS (i.e. Ci total) or activity per unit weight of the PHTS coolant (i.e. μCi/kg).

the GFP computer system. These summary files contain the summation spectra of 16 collection periods and can be used for a more detailed analysis if necessary. For instance, they can also be analyzed for additional radionuclides besides the key ones that are regularly monitored.

2.1.2 Grab Sampling

In addition to continuous monitoring of PHTS radionuclide activity by the GFP system, coolant activity in the PHTS is also routinely monitored by the site chemical laboratory. Depressurized samples of the PHTS coolant are routinely taken and gamma spectrometric analyses are performed in the laboratory for iodine and noble gases (i.e. ^{88}Kr, ^{133}Xe & ^{135}Xe). The monitoring frequency is increased when radioiodine concentration in the PHTS reaches certain pre-set values .

Since the samples are depressurized, measured concentrations of noble gases do not generally represent their absolute concentrations in the PHTS because of effervescence. However, for soluble radionuclides such as iodine, the measurements represent accurate activity level of the PHTS.

2.2 Localization Capability

Once the presence of a failed fuel bundle is suspected in a Unit, the Delayed Neutron Monitoring (DN) system is used to locate the specific channel containing the defect.

The DN system functions by measuring emitted delayed neutrons in the PHTS. Delayed neutron emitters are produced by neutron activation products (such as ^{17}N) and fission products released by failed fuel elements (such as ^{137}I and ^{87}Br). To eliminate the contribution of activation products to the total signal, a delay coil is installed in the sampling lines.

It should be pointed out that initiation of fuel defect in a Unit could also be detected from DN signals. Typically, signals from the DN and the GFP as well as data from grab samples can all be used simultaneously to determine the occurrence of a failed fuel bundle in a Unit.

3.0 ANALYTICAL TOOL

Given the time required to positively identify the channel containing failed fuel, a Unit may need to operate a period of time before removal can be achieved. Under continuous irradiation, secondary defects may occur due to hydriding, leading to increase in the rate of fission product release into the PHTS. Also when operating with a failed fuel bundle, the iodine released can raise the coolant activity close to the limit if the channel containing the fuel bundle is refueled or shifted to a low power position or possibly be discharged coincidentally from the Unit. There may also be concerns when starting up a Unit with failed fuel because of the potential for the defect degradation.

Considering these potential concerns, it is important to develop analytical tools that can be used to interpret iodine evolution in the PHTS due to fuel failure occurrence using GFP online measurement data. Such a capability will serve to help manage PHTS iodine concentrations within acceptable levels while localization of the failed bundle continues with the DN system. For instance when a Unit is restarted with an existing failed fuel in it, degradation of the defect resulting in higher release rates of iodine may thereaten its operation if the coolant activity is approaching the iodine limit. Shutting down a Unit makes failed bundle localization remarkably difficult (given that localization techniques are effective only at power).

This is the kind of capability provided by the recently developed software tool (STAR) for analysis of on-line fission products data. STAR (Steady-state and Transient Activity Release), which is implemented in both FEMLAB and C++ solves a coupled system of partial differential equations representing the mass conservation of fission products in the fuel pellet, the fuel-to-sheath gap and the PHTS coolant (detailed of these conservation equations are presented elsewhere [1]).

The input parameters required by STAR are as follows:

- the coolant purification flow rate (normalized by PHTS mass)
- fuel element linear power rating (kW/m) and
- gap escape-rate coefficient (s^{-1}).

For releases in steam, the gap escape rate coefficient ν for iodine depends on defect size and the transport path length to the defect site as follows [2]:

$$\nu = \frac{2n\alpha}{l} \qquad \text{(E-1)}$$

where l is the fuel stack length (m), α (m/s) is a surface exchange coefficient between the gap and coolant and n =1 or ½ depending on whether the defect is a mid-rod defect or an end element defect. For a predictive simulation, n is usually assumed as 1. Based on in-reactor experiments, α can be directly related to defect area (i.e. fuel exposure) E (mm^2) by the following correlation [2]:

$$\alpha = 10^{0.7046\log E - 7.5173} \qquad \text{(E-2)}$$

Hence, the value of the gap escape coefficient ν is related to defect size by the following empirical relationship:

$$E = \log^{-1}\left(\frac{\log\left(\frac{\nu \times l}{2n}\right) + 7.5173}{0.7046}\right) \qquad \text{(E-3)}$$

It should be noted that this relationship only applies to the escape rate coefficient for releases from steam-filled gaps. When condensation takes place in the gap as a result of shutdown or bundle shift to a low power position, the escape rate coefficient in water (usually specified as *k*) is often up to 3 orders of magnitude bigger than ν.

With the input parameters specified, STAR calculates as a function of time, radionuclide activity inventory in the fuel-to-sheath gap and in the PHTS coolant. For noble gases, the gap escape rate coefficient is not a function of defect size; it only reflects the transport path length and defect geometry. Experimentally determined values of ν for iodine (based on data from Chalk River Laboratories) ranged from 6.790×10^{-8} s^{-1} (for a small-'tight'-defect) to 1.814×10^{-4} s^{-1} for a very large defect. For noble gases, ν ranged from 8.420×10^{-6} s^{-1} to 2.314×10^{-4} s^{-1} [2].

3.1 Key parameters and their effects on PHTS coolant activity evolution

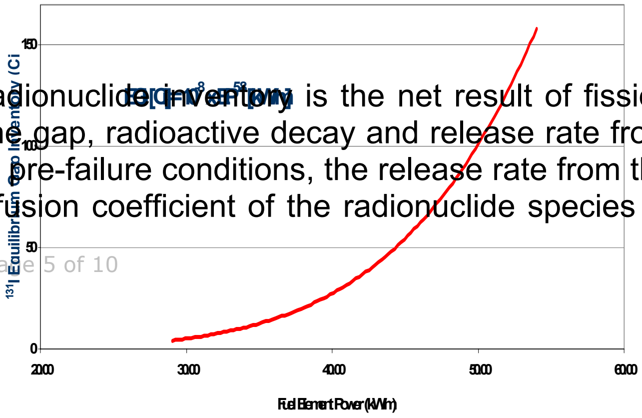
The parameters governing radionuclide activity release into the PHTS following fuel failure occurrences are interrelated. To better understand the behavior of radionuclide releases from failed fuel bundles, it is important to consider the relationship between fuel-to-sheath gap inventory, fission product release rate to coolant, defect size and element power.

3.1.1 Pre-failure conditions

In pre-failure conditions, the fuel-to-sheath gap radionuclide inventory is the net result of fission product release rate from the fuel pellet to the fuel-to-sheath gap and radioactive decay. The release rate from the fuel pellet to the gap is a function of the diffusion coefficient of the radioactive species of interest. The diffusion coefficient can be estimated from the knowledge of the element power (which defines pellet temperature) while radioactive decay is a function of the half-life of the specific fission product. Therefore, for an element of a certain power rating under irradiation for a certain period of time, one can calculate the total inventory of a radionuclide (with a known half-life) in the fuel-to-sheath gap.

3.1.2 Post-failure conditions

Following fuel sheath failure, the gap radionuclide inventory is the net result of fission product release rate from the pellet to the gap, radioactive decay and release rate from the gap to the coolant (PHTS). As under pre-failure conditions, the release rate from the pellet to the gap is a function of the diffusion coefficient of the radionuclide species of

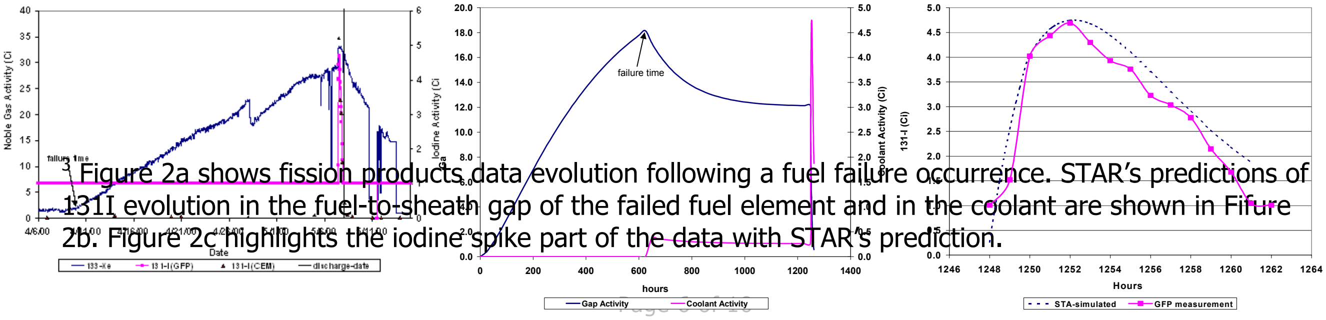


interest. However, following fuel sheath failure, the fuel is exposed to oxidation, hence the diffusion of fission products from the pellet becomes significantly enhanced. Since the amount of fission products released into the PHTS is determined by the inventory available for release from the gap once sheath failure occurs, the release rate here is calculated using oxidation enhanced diffusion coefficients (see Figure 1 for estimated variation of ^{131}I equilibrium activity in the gap with fuel element power rating, assuming diffusion coefficient of oxidized fuel).

In general, the time evolution of radionuclides in the PHTS coolant following fuel sheath failure occurrence can be calculated from the knowledge of fuel element power, apparent half-life (sum of decay constant and ion exchange PHTS purification rate) and release rate to coolant. For all Units, information on ion-exchange purification rate is readily available in the PI database, and for radionuclide species of interests the decay constants are known. The two variables to be determined are the element power and the release rate to coolant. When the gap is filled with steam, the release rate of iodine into the PHTS directly depends on the size of the defect. However, when the steam in the gap condenses, the release rate of iodine into the coolant becomes much larger because mobility of iodine species in water is about three orders of magnitude larger than in steam. Condensation takes place when the fuel-to-sheath gap temperature is lower than the corresponding saturation temperature. This can happen when the Unit is shut down or the failed element is shifted from a high power position to a lower power position.

For noble gas species, the release rate from the fuel-to-sheath gap into the PHTS coolant is independent of defect size; it only depends on the failed element power and on the defect geometry.

Relatively accurate estimates of the power of the failed element and the size of the defect are sufficient to simulate measured ^{131}I activity in the PHTS coolant and to predict future evolution following failed fuel occurrence. Until now, attempts to simultaneously estimate the power of a failed element and the size of defect have not been successful because such attempts have depended on steady-state coolant activity analysis. Using steady-state coolant activity analysis, several possible combinations of element power and defect size will produce the same measured coolant activity evolution. With the capability of STAR to perform transient calculations, both of these parameters can now be characterized simultaneously (see Figure 2[3]).



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[3] Figure 2a shows fission products data evolution following a fuel failure occurrence. STAR's predictions of 131I evolution in the fuel-to-sheath gap of the failed fuel element and in the coolant are shown in Fifure 2b. Figure 2c highlights the iodine spike part of the data with STAR's prediction.

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

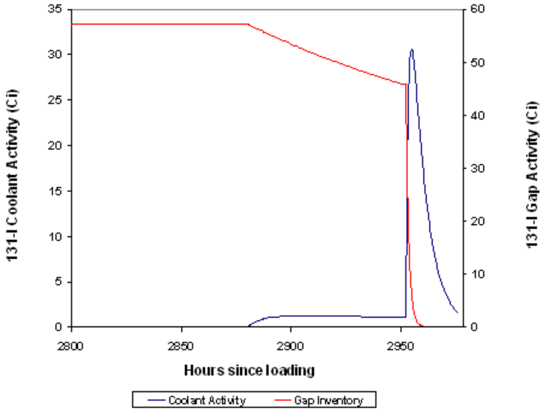
Figure 2: Comparison of STAR simulated 131I evolution with on-line data

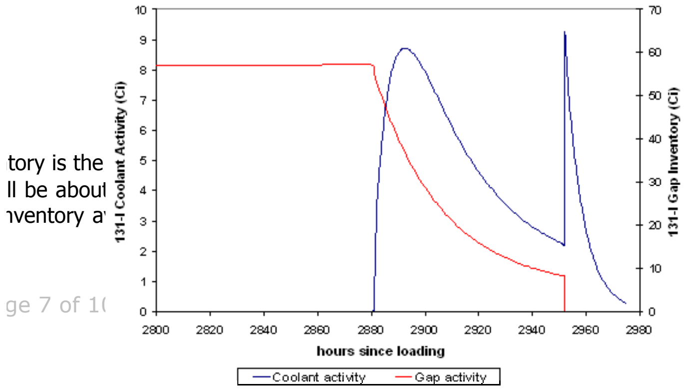
3.2 Numerical Illustration

To illustrate the effects of defect size and release rates, Figure 3 compare two examples (simulated using STAR) of coolant and fuel-to-sheath gap activity evolution following the failure of an element in a high power position. These figures show how ^{131}I evolved in the gap pre-failure[4]. The figures also show how ^{131}I activity evolved in the coolant due to diffusional releases and gap washout following fuel failure. The hypothetical element simulated was in a low power position for a period of 60 days (power rating of 35 kW/m) before being shifted to a high power position (power rating of 45 kW/m). After spending another 60 days in the high power position the element sheath was assumed to fail and fission products were released into the PHTS for three days before the fuel was discharged (or the Unit was shut down). For the first example shown in Figure 2a, the size of the defect is small resulting in a very low rate of ^{131}I release into the PHTS during the first three days following fuel failure occurrence, hence only a slight reduction in the fuel-to-sheath gap. When the fuel was discharged (or the Unit was shut down), the remaining ^{131}I inventory in the gap was released very rapidly into the PHTS (because of condensation) producing an iodine peak value of 30 Ci.

On the other hand, for the same element with a larger defect size (Figure 2b), the release rate of ^{131}I into the PHTS at the time of failure was much higher but the iodine peak produced on condensation was only 9 Ci. In the second example, the ^{131}I inventory in the fuel-to-sheath gap was depleted much faster following the failure occurrence because of the large defect size, leaving a much reduced inventory for release when the steam in the gap condensed to water (see Figure 2c-comparision of both cases). For both of these examples, an ion-exchange purification rate of 10 kg/s was used.

These two examples indicate the effect of defect size on coolant activity release into the PHTS coolant after a fuel failure occurrence. For a failed fuel with a large defect due to the high release rate on failure initiation, one might not observe any significant iodine release when the Unit is shut down or when the failed fuel gets discharged. On the other hand, it is highly likely to observe iodine spiking due to gap washout when a failed fuel with a small defect is discharged from the Unit or when the Unit is shut down.

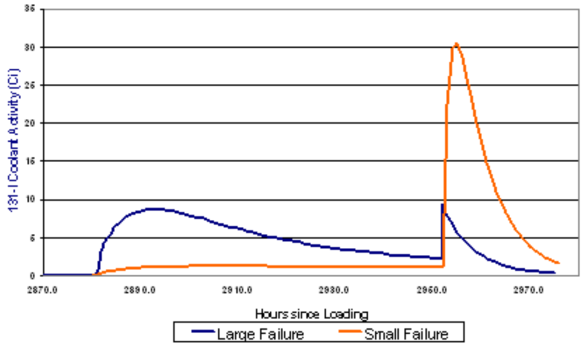




(a)

(b)

Figure 3: Illustrative simulations of ^{131}I evolution in the fuel-to-sheath gap and the PHTS following fuel failure with a small (a) and large (b) defect sizes <u>and (c) a comparison of cases (a) and (b).</u>



(c)

4.0 RAMIFICATION FOR UNIT OPERATIONS

The possibility of forcing a Unit shutdown due to high iodine coolant concentrations is more likely when the activity increase is caused by gap-washout than when it is caused by diffusional releases from the initiation of a new fuel or from degradation of an existing one. Since failed fuel localization and removal is much more difficult with the Unit shutdown, being able to keep the Unit at relatively high power while ensuring that iodine OP&P limit is not violated is important. The new analytical tools that have been developed can be used proactively to advice operations whenever a failed fuel is suspected to be present in the Unit. With these tools the following are possible:

- Iodine releases that occur as a result of gap washout (i.e. due to condensation in the fuel-to-sheath gap of a failed fuel) can be distinguished from iodine increases due to failed fuel degradation or the initiation of new defects, by calculating the source release rate (see Reference 1).

- Using STAR as a predictive tool, coolant activity levels that will be reached in a steady-state situation or during iodine transient (at a given reactor power and purification flow) following a fuel failure occurrence, can be estimated. This estimation can be done by adjusting the gap escape rate coefficient and the failed element power to fit measured coolant activity data from GFP or grab samples. Such prediction can provide an indication of the available time for discharging the failed fuel before the limit is reached or how much the reactor power can be decreased to allow for unlimited time for the localization of the channel containing the failed fuel. For instance Figure 4 shows the effect of reactor power on ^{131}I equilibrium concentration in the PHTS for given defect sizes, as predicted by STAR. This calculation shows that when the Unit is derated from 93%RP to 80%RP, ^{131}I equilibrium coolant activity decreases by 56%. In general, a reduction in reactor power of about 10% causes iodine level in the PHTS to reduce by as much as 50%.

- A simulation of iodine releases from failed fuel bundles under various Unit startup scenarios can be used to develop a set of guidelines to advice operations when restarting a Unit containing a previously failed fuel. This will enable power to be raised without concerns of reaching the iodine limit. For instance, as shown in Figure 5, by assuming a conservative number of failed fuel in a Unit with typical defect sizes and a certain reactor power (to which power is instantaneously ramped), the time evolution of iodine after startup can be estimated. This figure shows that after about 12 hours at the given power (in this case 80%RP), the coolant activity is not expected to have exceeded 8 μCi/kg. This value can be used as a check to determine if at full power, iodine equilibrium value will exceed the iodine limit. If the measured coolant activity is higher than expected, further power raise can be delayed until the failed fuel is discharged or a better assessment of the coolant activity can be performed.

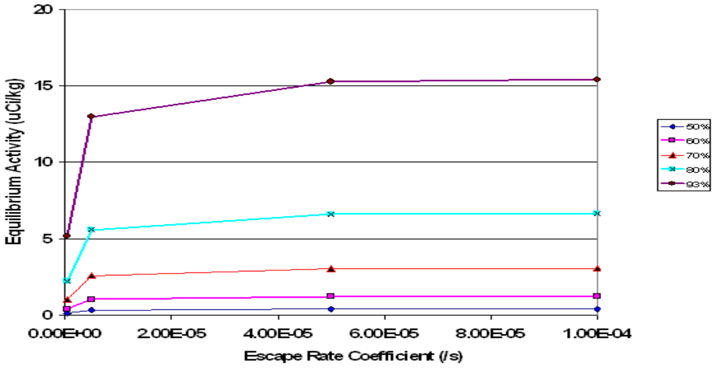


Figure 4: Variation of 131I activity in the PHTS at equilibrium with gap escape rate coefficient

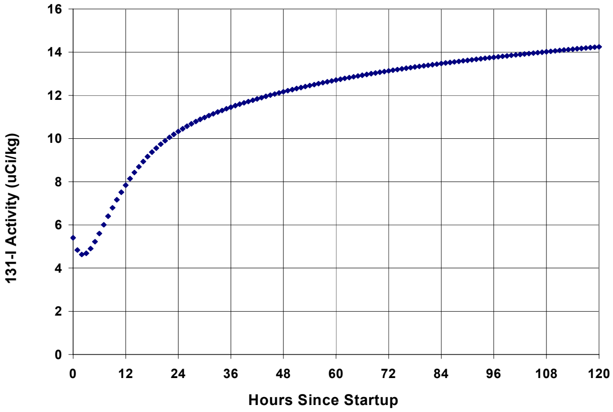


Figure 5: Prediction of ^{131}I evolution with time after startup based on releases from 2.5 failed fuel bundles at 45kW/m power rating.

5.0 CONCLUSIONS

PHTS Fission products data collected on-line can be used in conjunction with analytical tools to characterize failed fuel. Given the failed fuel element power and indication of defect size. Possible future evolution of iodine in the PHTS under different scenarios can be estimated to enable proactive decision making either during a Unit startup or during on-power operation thereby extending the time window for localizing a failed fuel bundle on power.

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