DEFECTIVE FUEL DETECTION IN CANDU 600s

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ABSTRACT

Fuel failures in CANDU 600s are detected and located by two independent on-power systems: the Gaseous Fission Product monitoring and Delayed Neutron Systems. The data generated by these systems can also be analyzed to:

- estimate the number of defective elements from Xe-133 activity concentrations,
- assess the defect condition from Xe-133/Kr-88 activity ratios,
- determine when fuel defects deteriorate and release uranium from delayed neutron signals, and
- evaluate in-core uranium levels from average delayed neutron signals.

Criteria presented in this paper, for deciding when to remove fuel failure, have been substantiated with operational data from Point Lepreau NGS.

INTRODUCTION

CANDU Pressurized Heavy Water Reactors are refuelled on-power with natural UO_2 fuel clad in collapsible Zircaloy-4 sheathing. Fuel performance has been excellent and the defect rate has been below 0.1% of the fuel bundles charged (1). With failed fuel detection systems, defective fuel can be located and removed using normal on-power refuelling with the reactor at full power. This permits the number of defective fuel bundles in core to be minimized in order to maintain a clean heat transport system. This enables reduction of occupational exposure to a low level, and contributes to high capacity factor of CANDU reactors.

Two failed fuel detection systems, which operate independently, are provided as standard equipment on each reactor unit: the Gaseous Fission Product (GFP) monitor and the Delayed Neutron (DN) system. This paper describes the two systems and demonstrates how the data provided by them are interpreted to determine:

- the number of defective elements in the core,
- the condition of the defects while at power,
- when defects begin to deteriorate and release uranium to the coolant, and
- the tramp uranium levels and distribution within the core.

The tramp uranium represents the amount that is not contained within the fuel and is free to recirculate and deposit within the heat transport system.

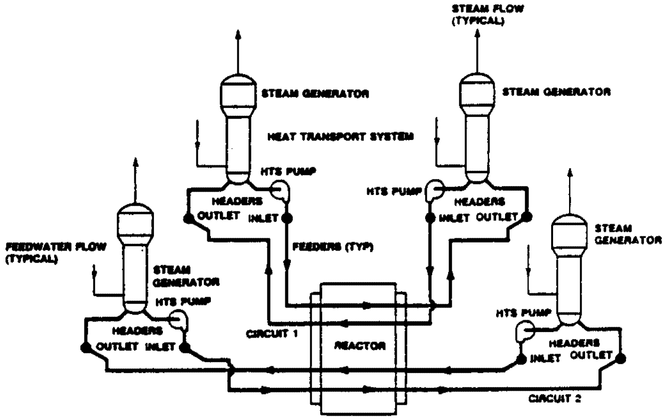

Figure 1 CANDU-600 Heat Transport System (HTS) The reactor is cooled by two identical loops, each with 190 fuel channels

DESCRIPTION OF GASEOUS FISSION PRODUCT (GFP) MONITOR

The GFP monitor is a computer controlled, high resolution gamma ray spectrometer. It is designed to operate continuously, repeatedly measuring the gamma ray activity of certain gaseous fission products, Xe-133, Kr-88 and Xe-135, and of iodine-131, present in continuous sample flows from each of the two heat transport system (HTS) loops (Figure 1). The two sample lines, one from each HTS loop, carry the coolant from the HTS pump discharge to the sample holders. The sample transit time is designed to be about 15 minutes to ensure sufficient time to remove unwanted F-17 by radioactive decay. A switch, located in the control room, is connected to air controlled valves that select the origin of the coolant in the sample tubes. Either loop 1, loop 2 or both loops together (without mixing), can be monitored. This enables the operator to determine which loop contains a defective fuel bundle.

The noble gas Xe-133 (81 keV)* is a long-lived fission product which has a high release rate from defective fuel. Its concentration when compared to that of a short-lived fission gas, such as Kr-88 (191 keV)*, provides some indication about the source, the extent of fuel sheath damage and the buildup of tramp uranium in the core.

Noble gas Xe-135 (250 keV)*, provides some information about the iodine release rates when high purification rates are removing fission products. This is due to the radioactive decay of I-135 to Xe-135 in the ion-exchange system. Since the noble gases are not retained by the ion-exchange system, the I-135 in the ion exchange system becomes a secondary source of Xe-135.

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* Dominant gamma decay energy

Radioiodine-131 (364 keV) is monitored due to its biological hazard. Since its concentration is suppressed by the ion-exchange system, it is not a reliable indicator for assessing fuel damage.

GFP DATA INTERPRETATION

The specific radioactivities for Xe-133 and Kr-88, measured in MBq per kilogram of coolant, are analyzed to determine the source of fission product release in the core. Three sources are defined.

1) A fast release defect - the release mechanism is primarily controlled by the diffusion process (4) of the gases through the fuel matrix with very little restriction due to the size of the defect.

2) A slow release defect - the release of the fission gases is restricted by a small defect hole size. A large fraction of the short-lived fission products are lost by decay during the delay between birth by fission and release to the coolant.

3) Tramp uranium - the fission gases are released promptly at birth by the recoil process (4). There is very little, if any, gas retention within the small amounts of tramp uranium distributed on the HTS surfaces within the core.

Table 1 summarizes the release characteristics for the source types during steady state and transient conditions. The following sub-sections give the basis for the numerical values and the application to CANDU 600 conditions.

TABLE 1

FISSION GAS RELEASE CHARACTERISTICS
FOR THREE SOURCE TYPES

	SLOW RELEASE DEFECT	FAST RELEASE DEFECT	TRAMP URANIUM
Steady State Conditions			
Xe-133 Fractional Release (F)	0.05 - 0.10	0.10 - 0.20	1.00
Corresponding Xe-133 Release Rate (R) in atoms/s	2×10^{12} to 4×10^{12} at 40 kW/m	4×10^{12} to 8×10^{12} at 40 kW/m	5×10^{10} per gram U
Fractional Release Dependence* on Natural Decay (λ)	b = 1.0	b = 0.5	b = 0.0
Transient Conditions			
Burst Release Fraction for Xe-133	0.05	0.05	0.0

* $F \alpha 1/\lambda^b$

Estimating the Number of Defective Elements and Tramp Uranium Levels From Steady State Release GFP Data

The mass balance equations governing the radio-isotope inventories within the fuel elements and heat transport system can be used to derive an expression for the number of defective fuel elements (n) in the core. During steady state conditions when the activity concentrations are at equilibrium and the reactor power and HTS pressure and temperature are constant, the relationship becomes:

$$n = \frac{\lambda^* Q}{R}$$

The system decay constant (λ^*), expressed as the inverse of seconds, is the sum of all losses due to natural radioactive decay (λ) and to removal by purification systems and coolant leakage. For the noble gases Xe-133 and Kr-88, the radioactive decay term dominates and the other losses can be neglected. The number of isotope atoms (Q) in the coolant can be determined directly from the measured coolant activity. The release rate (R), in atoms per second, from one defective element can be estimated from experimental irradiations of typical power reactor defects, or from operational experience.

Generally, the release rate for one defective element is expressed as:

$$R = (F)\ fY.$$

The source term (fY) is the product of the decay chain yield (Y), in atoms per fission, and the fission rate for the fuel element (f), in fissions per second, which is power dependent. The (F) term is the fractional release, or release-to-birth rate ratio, commonly used in the literature.

In experimental irradiations at Chalk River Nuclear Laboratories (CRNL), the fractional release for Xe-133 varied from 2 to 5% for a drilled hole defect in a fuel element operating at 48 kW/m(2). In another CRNL test at 55 kW/m, it varied from about 5 to 17% for fuel elements having either drilled holes or a machined slit (3).

In Ref. 11, the fractional release for Xe-133 was arbitrarily set at 5 to 10% for a slow release defect, at 10 to 20% for a fast release defect, and at 100% for tramp uranium in the core as given in Table 1. Using these F values, one defective element in the CANDU 600 core, operating at 40 kW/m, will account for the following Xe-133 activity concentrations:

- 17-34 MBq/kg for a slow release defect, and
- 34-68 MBq/kg for a fast release defect.

Also, tramp uranium distributed uniformly in the core and irradiated at the average neutron flux level, will yield:

- 0.8 MBq/kg per one gram of uranium.

These predictions are based on a HTS heavy water inventory of 122 Mg and an energy yield of 200 MeV/fission.

Estimating the Number of Defective Elements From Transient Release GFP Data

Fission gases can escape in a short-lived burst from a defective element in two different transient conditions. From the transient release characteristics it is possible to estimate the number of defective elements. The first condition arises as a result of a sudden change in HTS pressure or temperature, or in operating power. A simplified mechanism for fission gas release associated with a power increase is as follows: the water present within the defective element flashes, expelling steam and fission products to the coolant. The release of fission gases for a power reduction, is thought to be related to the thermal cracking of the UO_2 pellet. The cracks allow gases to escape from the fuel matrix and eventually through the defect hole. The second type of burst occurs due to the nature of the defect rather than loop conditions. This happens when a portion of the free fission gas inventory is released to the coolant in one burst at the time of failure. In both situations the short burst of activity is assumed to be governed by the same fission gas release characteristics.

During the burst, the release rate far exceeds the normal loss rate terms in the mass balance equations and the losses can therefore be neglected. From the mass balance equations, an expression can be derived for the number of defective elements in the core:

$$n = \frac{\lambda \, \Delta Q}{F_t \, fY}$$

The change in isotope gas inventory within the coolant (ΔQ) is determined directly from the increase in the activity concentration. The F_t term is defined as the transient or burst release fraction. It is equal to the fraction of the total isotope inventory within the defective element released during the burst.

In Ref. 11, the burst release fraction for Xe-133 was set at 5% for a defective element operating at 40 kW/m in a CANDU 600. The corresponding Xe-133 activity concentration is about 20 MBq/kg. This quantity is used for estimating the number of defects in the core.

Assessing the Defect Type From GFP Concentration Ratios

The dependence of fractional release (F) on the inverse of λ^b is a well established technique for assessing the source of the coolant activity (5,6). For tramp uranium within the core, all fission gases are released promptly at birth, causing F to be independent of the decay constant. The exponent b is equal to zero. For defective fuel elements, the fission gas release is primarily governed by the diffusion process for fast release defects, or by the hole size for slow release defects. In both cases, there is a delay between birth by fission and release through the hole. The portion of inventory available for release to the coolant depends on this time delay and on the decay half-life of the noble gas. Therefore, the fraction of the inventory released from the fuel is higher for the longer lived gases and the exponent b is positive. For data interpretation purposes, a value of 0.5 is assigned to b for a fast release defect and 1.0 for a slow release defect.

These relationships can be useful for comparing the concentrations of long-lived Xe-133 (5.3 day half-life) with short-lived Kr-88 (2.8 hour half-life).

Assuming negligible losses at equilibrium other than those due to natural decay, the activity concentration ratio for Xe-133 to Kr-88 can be expressed in terms of the chain yields, decay constants and exponent b:

$$\frac{[\text{Xe-133}]}{[\text{Kr-88}]} = \frac{Y_{xe}}{Y_{kr}} \left(\frac{\lambda_{kr}}{\lambda_{xe}} \right)^b$$

= 2 - 3 for tramp uranium
= 12 - 20 for a fast release defect
= 80 - 130 for a slow release defect

The upper end of each range reflects the adjustment on the chain yields due to plutonium buildup at high burnup.

The Xe-133 to Kr-88 activity concentration ratio can be a useful technique for assessing the defect type, but only for certain operating conditions. Firstly, the activity concentrations must be at equilibrium. Equilibrium is approached when the fission gas within the fuel defect builds up to its equilibrium inventory at steady power. This is normally achieved when the fuel defect operates at steady power without further degradation for about three decay half-lives of Xe-133, or about two to three weeks of steady operation. Secondly, the presence of tramp uranium in the core provides a source of fission gas that desensitizes the ratio technique as shown in Figure 2. Defect types can be distinguished only when the loop contains small amounts of tramp uranium, about 3 grams within the core boundaries. Consequently, the ratio technique should only be used under specific conditions.

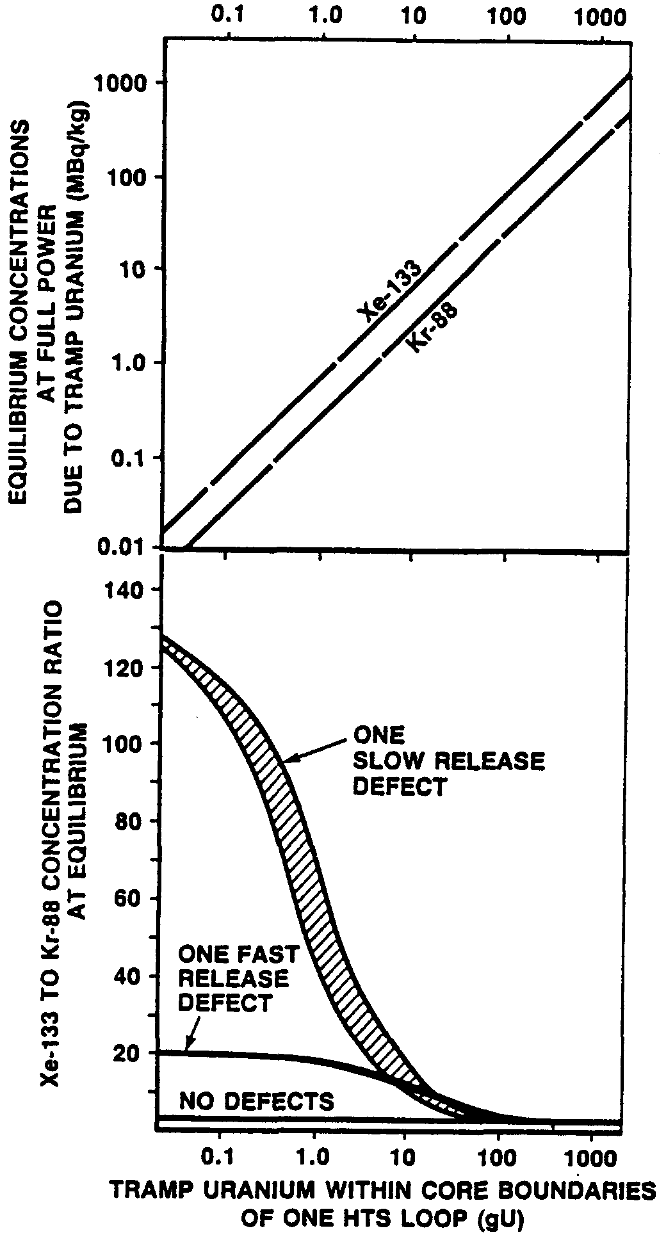

Figure 2 Graphs showing the effects of Tramp Uranium on:
a) the equilibrium activity concentrations of Xe-133 and Kr-88, and
b) Xe-133 to Kr-88 concentration ratio for a slow and a fast release defect

DESCRIPTION OF DELAYED NEUTRON (DN) SYSTEM

The DN system has two basic functions: to locate the fuel channel containing the defective fuel, and to locate the position of the defect within the fuel column (11). The data generated can also be analyzed to determine when defective fuel deteriorates and releases uranium to the coolant. Sampling lines from each of the 380 fuel channels carry coolant to the sample coil arrays in two water-filled moderator tanks, one in each scanning room. Six BF_3-filled neutron detectors in each room are positioned by their carriage and lowered into the sample-coil dry wells. The data are collected during the preset counting time and analyzed by an on-line computer. The detectors are raised and repositioned in sequence until all channels have been scanned. Computer-controlled or manual operation is done from a separate room in the reactor building (7). One complete DN scan requires only a few hours and is normally done once every one to three weeks.

The design of the sampling lines incorporates a deliberate 50 second delay to eliminate interference from unwanted activation products. These are the photoneutron producing nitrogen-16 (7 second half-life) and neutron emitting nitrogen-17 (4 second half-life). This leaves a high relative concentration of neutron-emitting fission products: iodine-137 (22.3 second half-life) and bromine-87 (55 second half-life). Background gamma radiation counts are rejected by electronic discrimination.

The parameters measured by the DN system are: $\bar{A}$ and $\bar{B}$, the average DN signal count rates of the channels in each of the two loop-halves, designated as loop-half A and B, and S, the DN signal count rates for a single channel. In practice, S is normalized to the loop-half average and is expressed as the discrimination ratio (DR) for a fuel channel:

$$DR = S/\bar{A}, \text{ or } S/\bar{B}$$

A channel containing defective fuel can be located by monitoring the historical trend of the discrimination ratio. Experience has shown that the channel usually contains a defect if its signal rises above the loop-half average plus three standard deviations, or if its DR exceeds 1.3 or 1.3 times its historical DR value. These are some of the main criteria that are being used to locate fuel channels with defective fuel (8,9).

Special single channel DN monitoring is done to locate the position of the defective fuel bundle within a suspect channel during refuelling at power. During refuelling, new fuel is inserted into the flow inlet end of the fuel channel by one fuelling machine. Through a series of moves, old fuel is removed at the flow outlet end by the second fuelling machine. By watching the changing DN signal as a fuel defect moves through the core, its position can be accurately determined as discussed in Ref. 10.

DN DATA INTERPRETATION

Taking advantage of the HTS loop configuration which divides it into two loop-halves, the measured parameters can be expressed in terms of the activity reduction factor (r), and the signal components due to tramp uranium and due to the fission products releases from defective fuel (10). The activity reduction factor is the portion of delayed neutron activity remaining after decay, during the time required for the fission products to travel from one loop half to the other.

$$r = e^{-\varepsilon T/2}$$

The effective half-life of the DN activity ($\ln 2/\varepsilon$) varies primarily with the natural half-lives of I-137 and Br-87. The recirculation time (T) for the CANDU 600 is estimated at 22 seconds. Therefore, r varies between the extremes of 0.71 for I-137 and 0.87 for Br-87 depending on their relative concentrations.

Ref. 10 shows how the DN signals can be represented by decreasing geometric series. Each term in the series represents the portion of signal due to the activity from I-137 and Br-87 on a given pass through the core. By summing the series, simple expressions can be derived for these measured parameters for the conditions as described in Ref. 11.

The derivations in Refs. 10 and 11 can be used to determine the total amount of tramp uranium (c) in the core for one loop, and the ratio of tramp uranium between two loop-halves of the same loops (a/b). These terms are expressed in terms of the loop half average signals ($\bar{A}$ and $\bar{B}$).

$$c = (\bar{A} + \bar{B})/60$$

$$a/b = (\bar{A} - r\bar{B})/(\bar{B} - r\bar{A})$$

Terms a and b are the average contributions to the signal from fission products on their first core pass from loop-half A and B, respectively. Provided no fuel failures are present, these terms are also proportional to the tramp uranium levels in their respective loop-halves. The units of "c" are normalized to 100% reactor power and to unity for a new core. CANDU 600 reactor experience indicates that a new core without fuel failures yields an average count rate of about 30 counts per second. The uranium in a new core comes from the small amounts deposited on fuel bundle surfaces during fabrication. This amount is estimated at less than one gram for the entire core.

These expressions provide a technique for determining the source of the uranium release. For example, if a defect in loop-half A begins to release uranium, then a/b will decrease due to the deposition of uranium downstream of the defect in loop-half B. The term "c" will also increase due to the uranium deposition in the core. Table 2 shows other possible scenarios.

TABLE 2

SOURCE OF URANIUM RELEASE DETERMINED FROM LOOP-HALF AVERAGE DN SIGNALS

	OBSERVED HISTORICAL TREND		
CATEGORY	a/b	c	SCENARIO
1	increasing	increasing	fuel defect in loop-half "B" is releasing uranium
2	decreasing	increasing	fuel defect in loop-half "A" is releasing uranium
3	increasing or decreasing	decreasing	no uranium release from fuel defects, tramp uranium is relocating within HTS

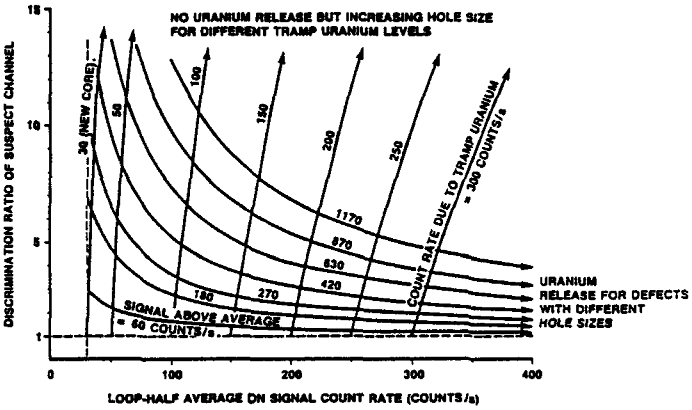

Figure 3 Predicted discrimination ratio behaviour for a defective fuel element deteriorating by:
a) increasing defect hole size, or
b) uranium release

Assessing the Condition of the Fuel Failure

Figure 3, reproduced from Ref. 11 shows the DR and loop-half average signal behaviour for a defective element in loop-half A, deteriorating under one of two hypothetical conditions:

1) no uranium release, but increasing defect hole size, and

2) uranium release, but stable hole size.

By predicting the DR behaviour of suspect channels for these two cases, the dominating type of deterioration of defective fuel can be determined from the DN data trends.

The first set of curves on Figure 3 represents the signal behaviour for a fuel defect that has no uranium release but has a defect hole that is increasing. The DR increases because the defect hole size is increasing, allowing fission products to escape at a higher rate. The loop-half average DN signals will also increase, but at a much slower rate due to the dilution and mixing effects in the loop and due to the activity decay during recirculation (11). The starting point for each curve is at DR = 1 at the time of failure. The corresponding starting value for $\bar{A}$ reflects the tramp uranium level in the loop.

The second set of curves on Figure 3 represents a fuel defect that has uranium release but has a stable defect hole size. At steady loop conditions, the hole size sets the fission product release rate, and S-$\bar{A}$ will be constant, as shown by each curve. However, the loop-half average signal will increase as the tramp uranium builds up in the core.

In practice, both types of deterioration are likely present simultaneously in defective fuel. However, by plotting the DN data trends in the manner suggested by Figure 3, it is possible to determine when one type dominates over the other.

It should also be noted that a certain portion of the uranium, released from a defective element may deposit immediately downstream within the core boundaries of the suspect channel. If this happens, the tramp uranium will act as a secondary source of fission products in that channel and it would not be possible to determine whether the increasing DR is due to tramp uranium buildup in the channel or due to increasing defect hole size.

POINT LEPREAU EXPERIENCE

Fuel Defect Summary

The first CANDU 600 reactor to go critical was Point Lepreau in July 1982. It was declared in-service in February 1983, and refuelling started in March. In 1983, four defective fuel bundles were discharged from four fuel channels as discussed in Ref. 10. In 1984 one fuel bundle was visually confirmed as having failed (11). In the first half of 1985, one more defective fuel bundle was discharged. These six fuel defects are summarized in Table 3. The operating histories of the first five are described in Refs. 10 and 11. The sixth is described below.

Channel S12 was refuelled on December 10, 1984 with a normal eight bundle shift. Several days later, its DR began to increase, coinciding with the increase in the Xe-133 activity concentration (Dec. 31). Since none of the new bundles had sufficient fission gas inventory to contribute to the Xe-133 transient release, the defect was believed to be in one of the four downstream bundles.

During refuelling on February 4, 1985, the single channel DN scan indicated bundle 9 or 10 was defective. Inspections done in the fuel bay confirmed that bundle 10 contained one defective fuel element, shown in Figure 4. Fuel management data indicated the defective element had operated at 32 kW/m since the time of failure.

Prior to the S12 fuel failure, the Xe-133 and Kr-88 activity concentrations were at equilibrium: about 2 and 0.6 MBq/kg, respectively. The Xe-133 to Kr-88 ratio was equal to about 3, indicating the main source of activity was due to tramp uranium in the core. Approximately 2 to 3 grams of tramp uranium were believed to be located in the core (Figure 2). Since the corresponding loop average DN signal, at the time, ranged from about 250 to 300 counts per second, the uranium contamination level was estimated at 8 to 10 times that of a new core. Combining both GFP and DN data, the contamination due to fabrication on new fuel is estimated at 6×10^{-9} to 10^{-8} grams of uranium/cm^2. This range is well below the new fuel specification; about a factor of 2 to 3 lower.

TABLE 3

VISUALLY CONFIRMED FUEL DEFECTS
AT POINT LEPREAU (TO MARCH 1985)

BUNDLE POSITION	NUMBER OF DEFECTIVE ELEMENTS AND PREDOMINANT LOCATION OF SECONDARY DAMAGE	ELEMENT LINEAR POWER (kW/m)	DISCHARGE DATE
Q16 - 2	2-3 - upstream end	8	83.4.19
G11 - 5	1 - upstream end	24	83.4.24
R09 - 3	1 - upstream end	38	83.4.25
R15 - 7	1 - middle	42	83.6.15
L22 - 10	1 - downstream end	17	84.6.22
S12 - 10	1 - upstream end	32	85.2.4

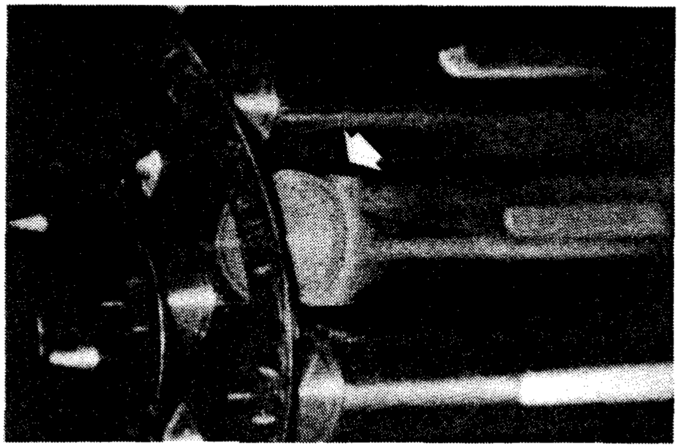

Figure 4 Defective fuel element for bundle 10 in channel S12 at Point Lepreau NGS showing secondary hydride damage (indicated by arrow) on an end cap at the upstream end of the bundle

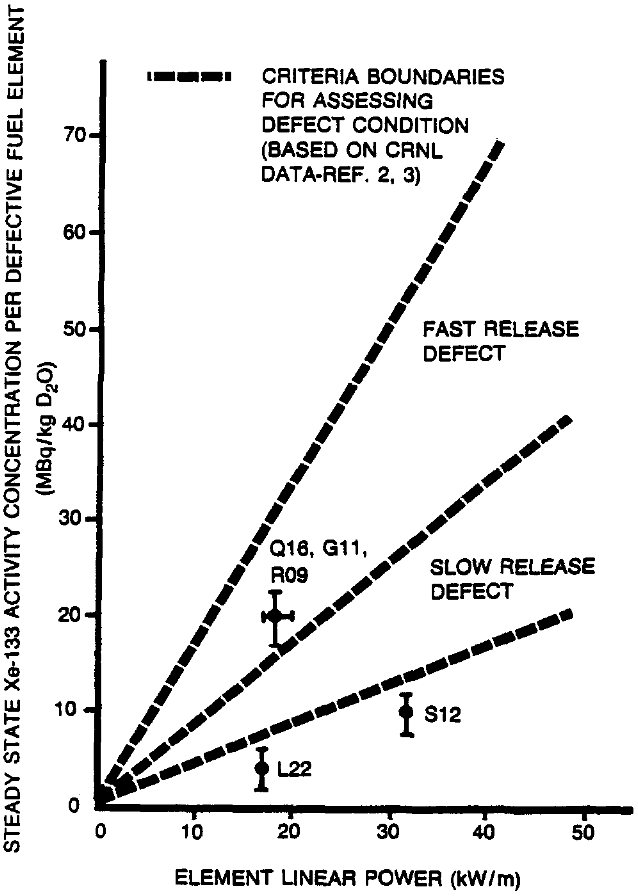

Figure 5 Steady state Xe-133 activity concentrations for fuel defects at Point Lepreau NGS

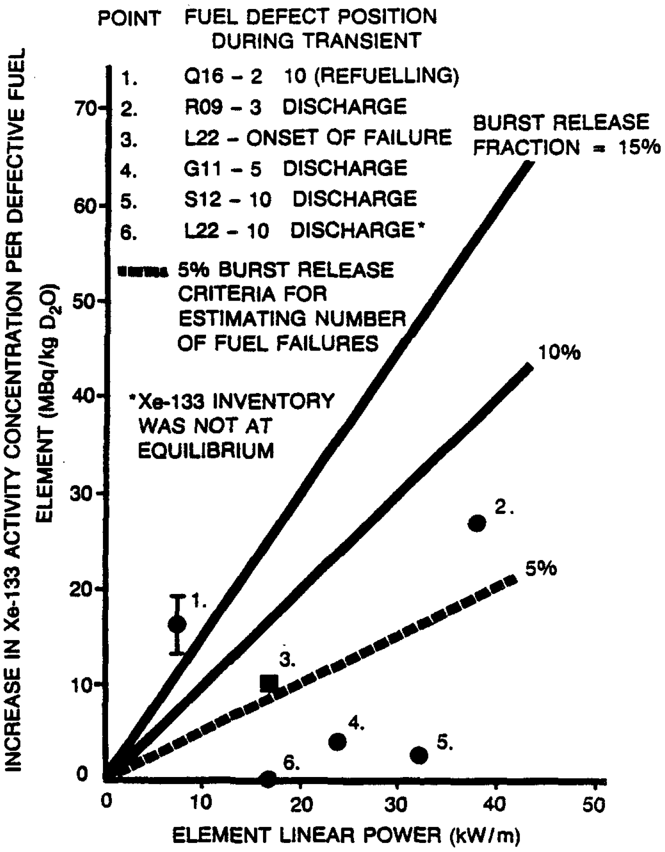

Figure 6 Transient Xe-133 activity releases from fuel defects at Point Lepreau NGS

Xe-133 Activity Releases Detected by GFP System

In Figure 5, the steady-state Xe-133 activity concentrations are plotted against the linear powers of the defective elements. The criteria for identifying defect types, included in this figure, suggest that the fuel defects in Q16, G11 and R09 were likely fast release defects, and the ones in L22 and S12 were slow release defects.

In Figure 6, the increases in Xe-133 activity concentration due to a transient release are plotted against the linear powers of the defective fuel elements. Most of these transients occurred while refuelling a channel containing a fuel defect. As shown, most of the burst release fractions were less than 10% of the total Xe-133 inventory within the corresponding defective element. The burst release fraction is more dependent on bundle position than on linear power. This observation supports the fission product release mechanism associated with water flashing to steam. A defective element near the channel inlet will contain more water, due to the coolant and saturation temperature profile along the channel, than fuel defects further downstream. As the fuel defect slides downstream during refuelling, the water flashes, expelling steam and fission products into the HTS. The amount of fission products released will likely depend on the amount of water inside the fuel element.

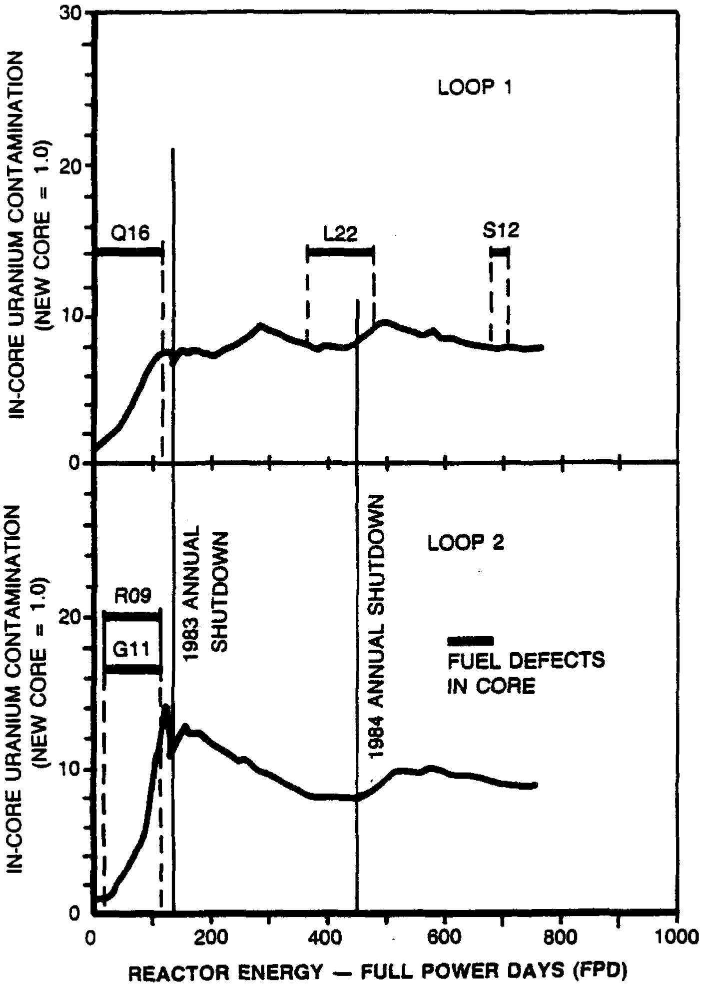

Figure 7 In-Core uranium contamination level for loop 1 and 2 — Point Lepreau

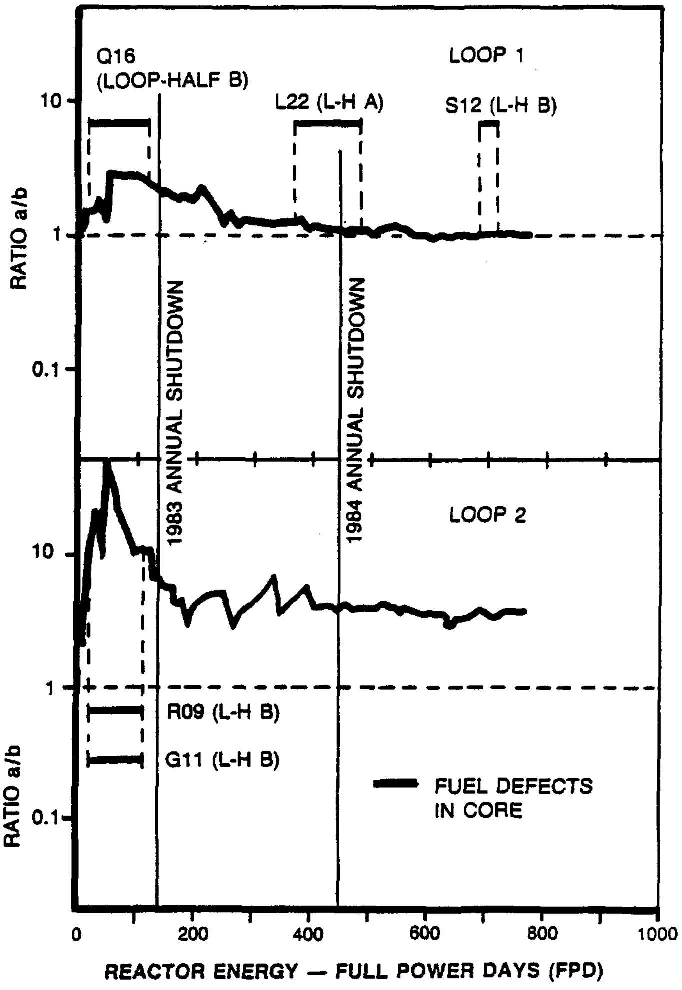

Figure 8 Ratio of In-Core uranium contamination between loop halves for loop 1 and 2 — Point Lepreau

Tramp Uranium Release as Detected by DN System

Figure 7 shows the total amount of tramp uranium (c), in the core for each loop, plotted against reactor energy. The term "c", normalized to one for a new core, is also proportional to the loop average delayed neutron signal, normalized to 100% reactor power. The duration each confirmed fuel defect resided in the core is also indicated on the figure. The dramatic increase in the tramp uranium level, shortly after the initial startup was likely due to the fuel defects in Q16, G11 and R09. For channels L22 and S12, there was no noticable change in the average signals, indicating very little, if any, uranium release from the defects.

It is interesting to note, the average DN signals increased slightly following long shutdowns. This may be due to some chemical/ temperature effect on uranium adsorption on HTS surfaces. Also, the marked increase in the average signal for loop 1 during the period from 200 to 300 FPD may have been due to the release of uranium from some other fuel defect that was not visually confirmed. During this period, transient releases of Xe-133 activity were also detected by the GFP system.

Figure 8 shows the ratio of in-core uranium contamination (a/b) between loop-halves for loop 1 and 2. The ratio "a/b" is a function of the loop-half average DN signals, as described earlier. The ratio increased significantly while the fuel defects were located in loop-half "B" of loop 1 (Q16) and in loop-half "B" of loop 2 (G11 and S12). This increase was due to the uranium release from the defects. Deposition in the core, first occurred downstream in loop-half A of both loops. After these defects were removed, the ratio decreased towards unity indicating the uranium distribution was becoming more uniform. This ratio was not affected by the presence of a fuel defect in L22 and S12, providing additional evidence that these defects did not release uranium.

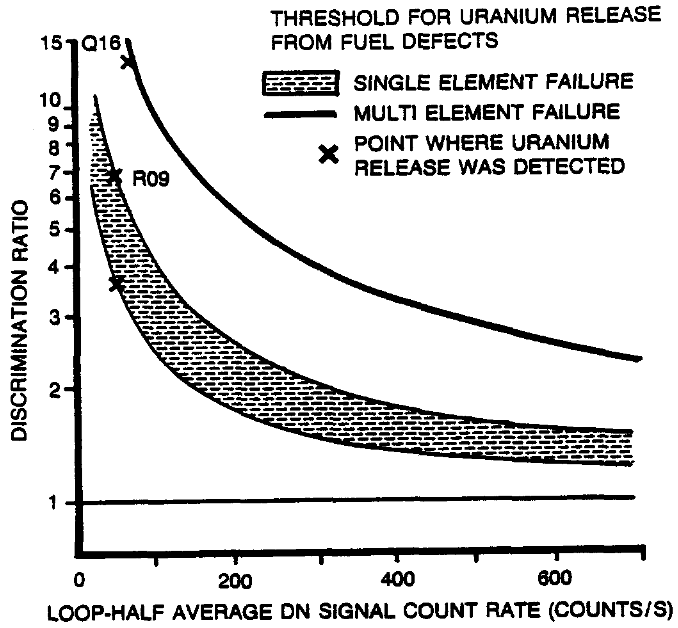

Figure 9 Thresholds for Uranium release for single and multiple fuel element failures.

Figure 9 is reproduced from Figure 3 showing uranium release thresholds derived from Point Lepreau experience. The first broad band curve represents the range of discrimination ratios and loop-half average signals where a single element fuel failure (R09 and G11) began to release uranium. The second curve represents the threshold for uranium release from a multi-element failure (Q16). The discrimination ratios for L22 and S12 before refuelling, fell below the first threshold.

CONCLUSIONS

The failed fuel detection systems in the CANDU 600 reactors are sufficiently sensitive to detect and locate small defects even in low power bundles.

The number of defective elements in the core can be estimated from steady-state or transient GFP data, in particular from Xe-133 activity concentrations. The first method is based on a fractional release of 5 to 10% of Xe-133 inventory under steady-state conditions for a "slow release defect", and 10-20% for a "fast release defect". The criteria are in good agreement with Point Lepreau experience. The second method is based on a burst release fraction of 5% of Xe-133 inventory under transient conditions for both defect types. The Point Lepreau data indicate that the magnitude of the transient release, during the refuelling of a channel containing a defect, is affected by bundle position. This variation supports a transient release mechanism associated with water flashing. The burst release can vary from 2% for for downstream to 2% for upstream bundles. The minimum number of defective elements can be estimated from the number of fuel channels with high DN signals, assuming one per channel.

The condition of the defective element (fast or slow release defect type) can be determined from the equilibrium concentration ratios of Xe-133 and Kr-88 provided:

- the HTS has low levels of tramp uranium, less than 3 grams in the core; and
- steady conditions are maintained for at least two weeks (3 decay half-lives of Xe-133).

The deterioration mode in terms of releasing uranium or increasing defect hole size can be assessed by analyzing DN data trends. Uranium release is indicated primarily by increasing loop average DN signals. Increasing defect hole size is characterized by an increasing DN signal for the suspect channel. Both techniques are useful but become less sensitive with increasing tramp uranium levels.

When the loop is free of fuel failures the Xe-133 activity levels can be used to estimate the tramp uranium levels. These levels relative to that of a new core can also be determined using loop-half average DN signals. The average signals also provide an estimate of the tramp uranium distribution between loop-halves.

Defective fuel should be removed when it begins to release uranium as indicated by increasing delayed neutron signals in the loop. Minimizing uranium release from fuel defects will not only maintain low radiation fields in the HTS, but avoid desensitizing the failed fuel detection systems. Fuel failures can be diagnosed by analyzing data from the two independent systems, provided low levels of tramp uranium are maintained.

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