FISSION PRODUCT RELEASE FROM HEU URANIUM-ALUMINUM ALLOY FUEL IN SLOWPOKE-2 REACTORS

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ABSTRACT

Increasing radiation fields due to a release of fission products in the reactor container of several SLOWPOKE-2 reactors fuelled with a highly-enriched uranium (HEU) alloy core have been observed. To investigate this phenomenon, samples of reactor water, and gas from the headspace above the water, have been obtained and examined by gamma spectroscopy methods for several reactors of various burnups. An underwater visual examination of a high-burnup HEU fuelled core has also provided information on the condition of the core.

INTRODUCTION

Following fabrication of the highly enriched uranium (HEU) fuel elements for the SLOWPOKE-2 research reactor, an external uranium contamination of the weld area was observed. This contamination occurred during the welding of end caps to the fuel pin meat, where some of the uranium aluminum alloy fuel was locally heated above its melting temperature and flowed out of the weld location. Although the weld area was machined later to remove such material, external contamination still remained (Figure 1) [1].

In subsequent operation of several HEU-fuelled SLOWPOKE-2 reactors, radionuclides have been observed in the reactor container water that surrounds the fuel, but not in the pool water which, in turn, surrounds the reactor container. The gamma radiation fields around the reactor can generally be attributed to this buildup of radionuclides, although no radiological hazard has resulted. At present, the radiation fields at the higher-burnup facilities reach levels sufficient to activate the medium-level radiation alarms positioned above the reactor container after only a few hours of operation at high power. Although these alarms were initially installed to detect a maloperation of the control rod or a loss of pool water shielding, they are now being triggered during normal operation at which point the reactors must be shut down.

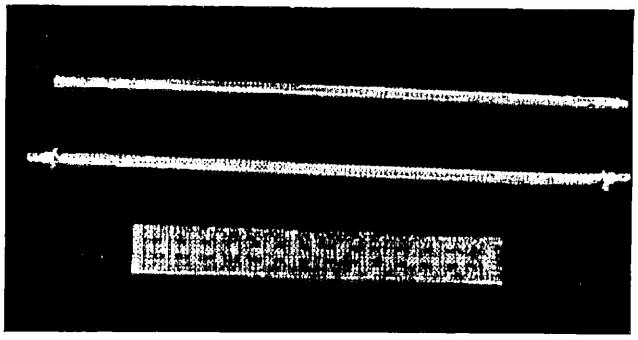

Figure 1

Photograph of the SLOWPOKE-2 uranium aluminide fuel pin as welded (bottom) and with the final machined end caps (top). (Courtesy of Atomic Energy of Canada Limited.)

By measuring the fission product release from the fuel to the reactor container water, it is possible to distinguish between release mechanisms and therefore to determine if the increase in radiation fields around the reactor is due to a loss of integrity of the fuel sheath.

This paper summarizes the results of studies conducted at the SLOWPOKE-2 facilities of the Royal Military College (RMC), the University of Toronto (U of T), Ecole Polytechnique (EP), and the Kanata Isotope Production Facility (KIPF). Although the reactor at RMC is the only one to be fuelled with a low-enriched uranium (LEU) core of uranium dioxide, it has provided a convenient location to commission the experimental equipment for fission product analysis. A visual examination of the uranium alloy core at EP with an underwater television camera has also been performed to provide additional information on the condition of the core.

SLOWPOKE-2 REACTOR DESIGN

The name SLOWPOKE is an acronym for Safe LOW POwer (K) critical Experiment, a research reactor developed by Atomic Energy of Canada Limited. This reactor is inherently safe since increasing temperatures would produce a negative effect on excess reactivity [1]. The reactor produces a flux of 1.0×10^{12} neutrons/cm^2/s and 20 kW of thermal energy at full power. Seven of these reactors are now operating across Canada and one is located at the University of the West Indies, in Kingston, Jamaica.

The SLOWPOKE-2 reactor is a tank-in-pool type of design with a light-water moderated core within a reactor container structure (see Figure 2) [2]. The surrounding pool of light-water serves as radiation shielding for research personnel and also as a secondary heat sink. Water purity is maintained by circulating

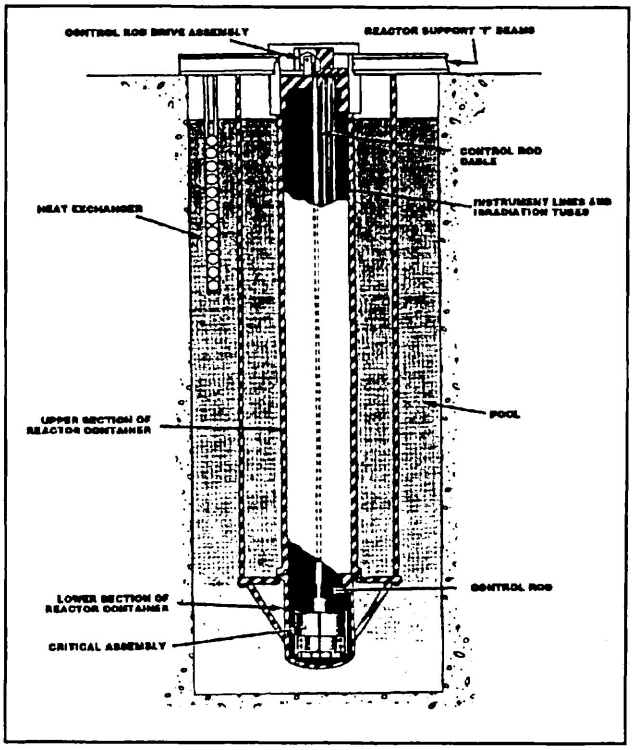

Figure 2

Reactor general assembly. (Taken from Reference [2].)

the container water through a series of deionizer columns on a weekly basis. Control of the reactor is maintained with a single control rod. The radiation monitors are located just above the reactor container (the medium-level alarm), above the reactor on the ceiling of the room (the area alarm), and beside the deionizer columns (low-level alarm). Generally, only the medium-level alarm prohibits continuous full-power operation.

Fuel Design

Of the eight operating SLOWPOKE-2 reactors, seven were fuelled with 93% U-235 enriched uranium aluminum alloy fuel pins coextruded with a 1050-aluminum cladding. The most recently commissioned SLOWPOKE-2 reactor (which is operating at RMC) is fuelled with low enriched uranium oxide fuel (20 % U-235), clad in Zircaloy-4. A comparison of the two types of cores is given in Table 1. Radiation fields associated with fission product release have been observed only at those reactors fuelled with the HEU core.

Table 1

A Comparison of the HEU and LEU SLOWPOKE-2 Cores[a]

	HEU Core (U of T, EP, KIPF)	LEU Core (RMC)
Fuel:		
Material	28 wt% U, 72 wt% Al UAl_4 in Al	UO_2
Enrichment (wt% ^{235}U in U)	93	19.89
Radius (mm)	2.11	2.083
Fuel Stack Length (cm)	22.0	22.7
Density (Mg/m^3)	3.40	10.6
Specific Heat ($J\ kg^{-1}\ K^{-1}$)	683	236
Thermal Conductivity ($W\ m^{-1}\ K^{-1}$)	171	4.67
Sheath:		
Material	Al-1050	Zircaloy-4
Outside Radius (mm)	2.62	2.63
Thickness (mm)	0.51	0.51
Density (Mg/m^3)	2.7	6.55
Specific Heat ($J\ kg^{-1}\ K^{-1}$)	903	290
Thermal Conductivity ($W\ m^{-1}\ K^{-1}$)	238	12.6
Core Description:		
Total Mass of ^{235}U (kg)	0.87	1.12
Number of Pins	317 (KIPF) 296 (EP) 298 (U of T)	198

(a) Taken from References 1 to 4.

EXPERIMENTAL DETAILS

Equipment

An analysis of fission products in the reactor container water and gas headspace at four SLOWPOKE-2 reactors has been performed by gamma ray spectroscopy methods using a GMX high purity germanium detector with a thin beryllium window (EG&G Ortec). Radiation shielding of the detector was provided by a transportable ensemble consisting of a lead brick castle supported by an aluminum frame.

Sampling Procedure

Due to the very low activity levels at the RMC reactor, it was necessary to count water samples for a minimum of four hours, and gas samples for eight hours. At the other reactors, gas and water samples were taken once per hour, and counted for 25 minutes to provide good counting statistics.

Gas Sampling. Each SLOWPOKE-2 reactor is equipped with a closed sampling line and pump (5 L/min) for the measurement of any hydrogen in the gas headspace above the reactor water. In order to obtain a uniform, well-mixed fission gas sample before counting, the pump was operated for ten minutes after which it was switched off and the sample counted. At RMC, a gas sample was obtained with a 50 mL syringe which was inserted into the hydrogen sampling port. For the other reactors, a 40 mL gas chamber was connected in line with the pump, and the sampling lines were then inserted into the gas headspace to form a closed system. The transport time from the headspace to the sample chamber was typically less than 30 s.

Water Sampling. The SLOWPOKE-2 reactor water purification system has a bypass loop through which one can obtain samples of reactor container water. The pump (with a flow rate of ~10 L/min), was run for two minutes in order to clear the dead space in the sampling line. At RMC, the water sample was obtained in an open graduated cylinder and then decanted into a Marinelli beaker. During this transfer, some degassing occurred. As such, the sampling procedure was modified for the U of T, EP and KIPF experiments with the use of a sealed, pressurized sample chamber (40 mL) connected in line with the sampling port.

Experiment Description

A brief summary of the operating parameters for each experiment is given in Table 2. The reactor in each experiment was run continuously at one-quarter power, producing a flux of 2.5×10^{11} neutrons/cm^2/s for approximately 100 h to allow most of the long-lived fission products to reach equilibrium in the reactor. The reactor was operated at this low power to maintain an excess reactivity. The radiation alarm monitor levels were recorded throughout the week so that these levels could be correlated with the fission product inventory in the reactor water.

EXPERIMENTAL RESULTS AND ANALYSIS

Concentration Calculation

The concentration in the reactor medium (water or gas) of a given isotope as a function of time can be calculated from the gamma spectra. In this calculation, the area of the peak of interest is evaluated with the MicroSAMPO analysis program [5] with the use of an energy calibration file, the detector efficiency and a shape calibration of the expected photo-peaks. The peak-search algorithm in MicroSAMPO will search for all peaks of a height which is greater than or equal to a specified number of standard deviations (sigma) of the Compton background. Typical peaks observed in the fission-product spectra were greater than 10 sigma as required for quantitative determination [6]. The count rate for the peak (gamma/s) was incorporated into a Microsoft Excel spreadsheet where the activity concentration of the isotope

Table 2: Summary of SLOWPOKE-2 Fission Product Experiments

Reactor	Date of Experiment	Test Description	Reactor Power (kW)	Radiation Monitor Levels (mR/h)			Coolant Outlet Temp (^{o}C)	Coolant pH
				Reactor	Deionizer (prestart-up)	Area		
RMC	5-9 Nov 90	Constant operation at 1/4 power	5	N/A	N/A	N/A	N/A	N/A
U of T	26-30 Nov 90	Constant operation at 1/4 power	5	8 - 10	N/A	0.08	28 - 33	N/A
	20-21 May 91	Transport time calculation at 1/4 power;	5	N/A	N/A	N/A	N/A	N/A
		Transport time and operation at full power.	20	40-100 (level recalibrated in Mar 91)	N/A	0.08 - 0.1	40 - 45	N/A
EP	25 Feb - 1 Mar 91	Transport time calculation;	5	N/A	4 - 6	N/A	27	N/A
		steady operation at 1/4 power;	5	2 - 3		0.05 - 0.1	27 - 34	
		Power ramp at end of test.	5	2 - 3		0.05 - 0.1	27 - 34	
			10	6		0.06 - 0.1	35 - 42	
			20	8 - 20		0.1 - 0.2	51 - 54	
KIPF	9 - 11 Apr 91	Transport time calculation;	5	0.4 - 0.6	2 - 4	0.4	24 - 28	N/A
		Power ramp at 1/4, 1/2, 3/4, and full power.	5	0.6 - 1.0		0.2 - 0.4	29 - 32	N/A
			10	2 - 4		0.4 - 0.6	36 - 41	N/A
			15	N/A		N/A	45 - 47	N/A
			20	2 -6		1 - 2	40 - 46	N/A
	13-17 May 91	Constant operation at 1/4 power;	5	0.8 - 1.5	4 - 6	0.4 - 0.6	28 - 39	5.5 - 6
		Water sampling at various heights in container (1-4 m) at end of test.	5	0.8 - 1.5		0.4 - 0.6	39	

N/A: Not Available

was calculated given the absolute gamma ray abundance, the time lag between the collection and measurement of the sample, and the counting time.

A list of activation and fission products observed in the reactor container water and gas headspace at the U of T reactor are given in Table 3. These isotopes are typical of those observed at the other HEU reactors.

Table 3

Observed Radionuclides at the U of T Reactor

A. Reactor Container Water	
Fission Products	
Noble Gases:	Kr-85m, -87, -88, -89
	Xe-133, -133m, -135, -135m, -137, 138
Halogens:	I-131, -132, -133, -134, -135
Alkali Metals:	Rb-88, -89, Cs-138
Alkaline Earth:	Sr-91, Ba-140
Noble Metals:	Mo-99, Tc-99m
Rare Earths:	Y-91m, La-140, -142,
	Ce-141, -143, Nb-95, Zr-95
Activation Products	
Noble Gases:	Ar-41
Alkali Metals:	Na-24
Actinides:	Np-239, U-239
B. Gas Headspace[a]	
Fission Products	
Noble Gases:	Kr-85m, -87, -88, -89, -90
	Xe-133, -133m, -135, -135m, -137, 138
Alkali Metals:	Rb-88, -89, Cs-138
Activation Products	
Noble Gases:	Ar-41
C. Deionizer Column[b]	
Halogens:	I-131
Alkali Metals:	Cs-137
Alkaline Earth:	Ba-140
Rare Earths:	La-140, Nb-95, Zr-95

(a) The alkali metals are present in the sample vial as a result of the radioactive decay of the noble gas species.

(b) From a previous gamma spectroscopy analysis [7].

The most significant difference between the various reactors is the absolute activity concentrations of the reactor water and gas as shown in Table 4. This table gives the absolute activity

Table 4

^{133}Xe Concentration in the Reactor Container Water and Gas Headspace (5 kW)

Reactor	Xe-133 Concentration[a] (MBq/L)		Time After Start-up (h)
	Water	Gas	
RMC	1.9×10^{-5}	1.4×10^{-5}	92
KIPF	0.08	0.06	72
EP	0.68	0.34	72
U of T	1.4	2.5	72

(a) The typical error is less than 10%.

concentration of ^{133}Xe after continuous reactor operation at one-quarter power. The activity at the LEU reactor (RMC), is at least three orders of magnitude less than that observed at the other HEU reactors. The fission products observed at RMC are most likely due to surface contamination from the original uranium traces deposited on the fuel pin external surfaces during fuel fabrication [8,9].

Transport Time Estimate

There is a delay between the creation of fission products in the core and their uptake at the sampling port. During this time, the activity of the short-lived fission products will have decayed. The transport time was therefore estimated by rapidly sampling the coolant at the start of a given experiment (i.e. every three minutes) and noting the time lag between the point at which the reactor had reached power and the first occurrence of the short-lived isotope, ^{138}Xe. (The reactor would generally reach the flux set point in one to two minutes.) Typical values obtained with this method for the various reactors ranged from about three to fourteen minutes, e.g. for the following analysis the transport time is taken to be six minutes at U of T and KIPF, and fourteen minutes at EP.

Release Rate Calculation

In order to determine the mechanism of release from the core, the release rate can be determined for the noble gas fission

products. Based on mass balance considerations in the closed reactor container, the release rates of fission gases from the fuel into the water (R_{fw}), and from the water into the gas headspace (R_{wg}), can be calculated from the activity concentration data [7]. The net rate of change of the number of atoms with respect to time of a given radioactive isotope in the water (N_w) is

$$dN_w/dt = R_{fw} - \lambda N_w - R_{wg} \quad (1)$$

where λ is the radioactive decay constant (s^{-1}). Similarly, the mass balance for the inventory in the gas headspace (N_g) is

$$dN_g/dt = R_{wg} - \lambda N_g \quad . \quad (2)$$

These inventories are related to the measured activity concentrations (C) as:

$$C = \lambda N/V \quad , \quad (3)$$

where V is the given volume of water above the core (1380 L) or the volume of the gas headspace (108 L) [2]. Hence, using the above relation, Eqs. (1) and (2) can be rewritten as

$$R_{fw} - R_{wg} = V_w \{(1/\lambda) dC_w/dt + C_w\} \quad (4)$$

$$R_{wg} = V_g \{(1/\lambda) dC_g/dt + C_g\} \quad . \quad (5)$$

In general, for the noble gas isotopes, the release rates from the fuel to the water (R_{fw}) are much greater than those from the water to the gas headspace (R_{wg}), i.e. $R_{fw} >> R_{wg}$ [10]. In this case, Eqs. (4) and (5) can be decoupled such that

$$R_{fw} = V_w \{(1/\lambda) dC_w/dt + C_w\} \quad ,$$

which can be equivalently written as:

$$dC_w/dt = \lambda R_{fw}/V_w - \lambda C_w. \quad (6)$$

If R_{fw} is relatively constant over the course of the experiment, the solution of Eq. (6) is given by

$$C_w(t) = (R_{fw}/V_w) \cdot (1 - \exp\{-\lambda t\}) + C_{wo} \exp\{-\lambda t\}, \quad (7)$$

where C_{wo} is the initial (measured) concentration in the water at the start of the experiment.

Equation (7) was fit to the measured concentration data, using a Marquardt-Levenberg algorithm [11] where R_{fw} was the single fitting parameter (see Figure 3). For isotopes with relatively long-lived precursors (e.g. ^{133}Xe and ^{135}Xe), Equation (7) was generalized to account for precursor effects in the container water.

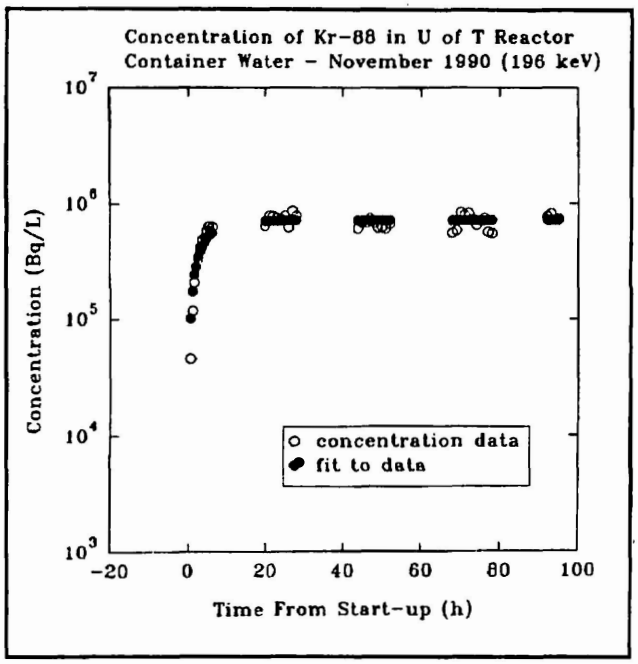

Figure 3

The concentration of Kr-88 at the U of T reactor.

MODEL DEVELOPMENT

When a fission fragment is created from the splitting of a ^{235}U nucleus, it is highly energetic (average kinetic energy of about 80 MeV) and can therefore travel a finite range before coming to rest in the uranium aluminide fuel meat where it would normally be contained. If, however, the fission product is created near the surface of some exposed portion of the fuel (such as at the uranium-bearing end weld line), it can be ejected directly into the surrounding coolant. Such a release can therefore occur by direct fission recoil. Alternatively, a fission fragment created deep inside the fuel will lose its kinetic energy, following which it may slowly migrate or diffuse through the fuel matrix and escape once it reaches the exposed surface.

Since recoil release is an instantaneous process, the release rate (R_{fw}) (in atoms/s) from the fuel pin into the coolant is independent of the half-life of the fission product so that [8]:

$$(R_{fw}/Y)_{rec} = \tfrac{1}{4}\mu(\Delta S/V)F \quad , \tag{8}$$

where $\Delta S/V$ = ratio of the exposed fuel surface to the total fuel pin volume (m^{-1})

μ = average fission-fragment range in the fuel (m)
Y = fission yield for a given radionuclide (atoms/fission)
F = fission rate per rod (fissions/s).

On the other hand, for a diffusion process, the release rate (R_{fw}) will depend on the half-life of the isotope [12]

$$(R_{fw}/Y)_{dif} = (\Delta S/S)\ 3(D_f'/\lambda)^{1/2}F \quad , \tag{9}$$

where $\Delta S/S$ = fractional surface area of fuel exposed to the coolant per rod
D_f' = effective diffusion coefficient for fission products in the fuel (s^{-1})
λ = radioactive decay constant (s^{-1}).

For example, a diffusion model has been employed in the STARS fuel performance code for the prediction of fission gas release in metal fuels [13]. At lower fuel temperatures, re-solution back into the fuel matrix will dominate so that if any gas bubbles are formed they will remain small, and gas release will therefore depend more on the behaviour of single gas atoms rather than on bubbles [13,14].

If both diffusion and recoil are important, Eqs. (8) and (9) yield

$$R_{fw}/Y = n\{(R_{fw}/Y)_{dif} + (R_{fw}/Y)_{rec}\} = a\lambda^{-1/2} + c \quad , \tag{10}$$

where n is equal to the number of defective fuel pins, $c = \frac{1}{4}\mu(\Delta S/V)(nF)$ and $a = 3(\Delta S/S)\cdot(D_f')^{1/2}(nF)$. The model in Eq. (10) has been fit to the measured release rate data in Figure 4. The meaured values of the short-lived isotopes have been corrected for radioactive decay during transport from the reactor core to the sampling port [10]. The fitting parameters (a and c) are listed in Table 5 for the HEU reactors. A relatively flat line in Figure 4 indicates that recoil is a dominant release mechanism for the short-lived isotopes.

Dependence of Release on Reactor Power

An alternate method for determining the mechanism of release is to investigate the dependence of the release rate (R_{fw}) as a function of the fission rate (F) (i.e. reactor power). As seen in Eq. (8) for a recoil process, the release rate varies linearly with the fission rate. On the other hand, fission products can also migrate by solid state diffusion at low fuel temperatures. Radiation-enhanced diffusion rates have been observed at these low temperatures due to the creation of defects in the solid lattice by fission fragments [15]. In this particular case, the diffusion coefficient (D_f') is proportional to the fission rate. Hence, inspection of Eq. (9) reveals that the release rate should vary as $F^{3/2}$. At higher fuel temperatures, the diffusion

Table 5

Fitting Parameters of Fission Product Release Model[a]

Reactor	Fitting Parameters[b]	
	a (fissions/$s^{1/2}$)	c (fission/s)
U of T	$6.3 \times 10^{7} \pm 25\%$	$2.0 \times 10^{10} \pm 17\%$
EP	$4.5 \times 10^{7} \pm 22\%$	$7.7 \times 10^{9} \pm 23\%$
KIPF	$7.2 \times 10^{6} \pm 44\%$	$3.3 \times 10^{9} \pm 22\%$

(a) Errors are quoted to one standard deviation.
(b) See Equation 10.

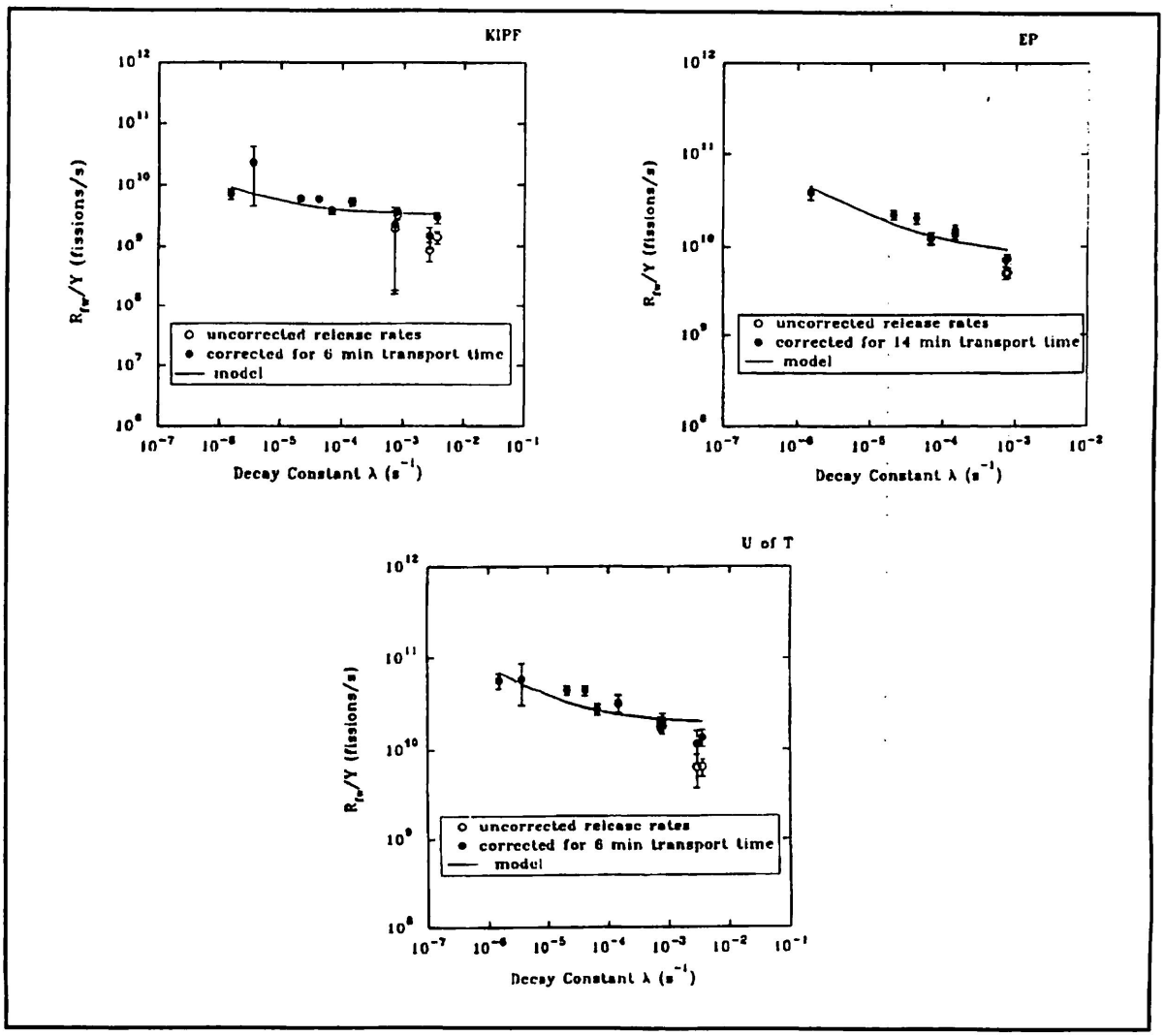

Figure 4

R_{fw}/Y versus λ plot for three HEU fuelled reactors.

coefficient will vary as an Arrhenius function of temperature, implying a stronger dependence on the reactor power [16].

For this investigation, the isotope, ^{138}Xe, was selected for monitoring since its half-life is sufficiently short to allow it to reach equilibrium conditions quickly at each power level. A linear variation of the release rate of ^{138}Xe (corrected for decay during transport) with reactor power is shown in Figure 5. Similar results were also observed for the other reactors. This dependence is indicative of a recoil release process.

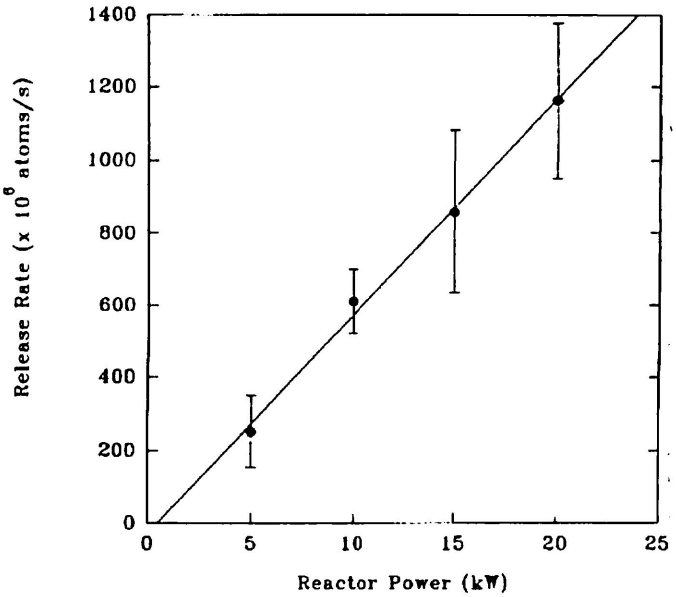

Figure 5

Release Rate of ^{138}Xe (fuel-to-water) at KIPF reactor as a function of reactor power.

In summary, recoil is an important release process from the fuel as evidenced by:

i) the (R_{fw}/Y) versus λ plots show a dominant recoil release component for the shorter-lived isotopes;

ii) the release rate of ^{138}Xe is linear with reactor power;

iii) the concentration model in Figure 4 assumes a constant rate of release that is consistent with a recoil process.

FUEL-SURFACE EXPOSURE

The average fuel exposure per pin can be determined by employing the recoil model in Eq. (8), where for a cylindrical pin of radius r and length ℓ:

$$R_{fw}/Y = \tfrac{1}{4}\mu(\Delta S)\, F_c/(\pi r^2 \ell) = c. \qquad (11)$$

Assuming that all pins are contributing to the release, F_c (=n·F) can be estimated from the average fission rate for the core. If the reactor is operating at 5 kW, and each fission event liberates 200 MeV of energy, then $F_c = 1.56 \times 10^{14}$ fissions/s. The range (μ) of the noble gas precursors [17] in the uranium aluminide fuel is calculated to be ~13 μm using the individual ion ranges and the Bragg combining law for the compound [18,19]. Using the fuel pin dimensions in Table 1, and the values of c in Table 5, the fuel exposure ΔS (per pin) can be determined from Eq. (11). As seen in Figure 6, the exposed area has been increasing with the accumulated flux-hours. The increase in the fission-product release is associated with the core burnup rather than the physical age of the reactor; the higher burnup U of T reactor has radiation levels approximately one order of magnitude greater than those at the University of Alberta (U of A) reactor even though both cores were commissioned at about the same time.

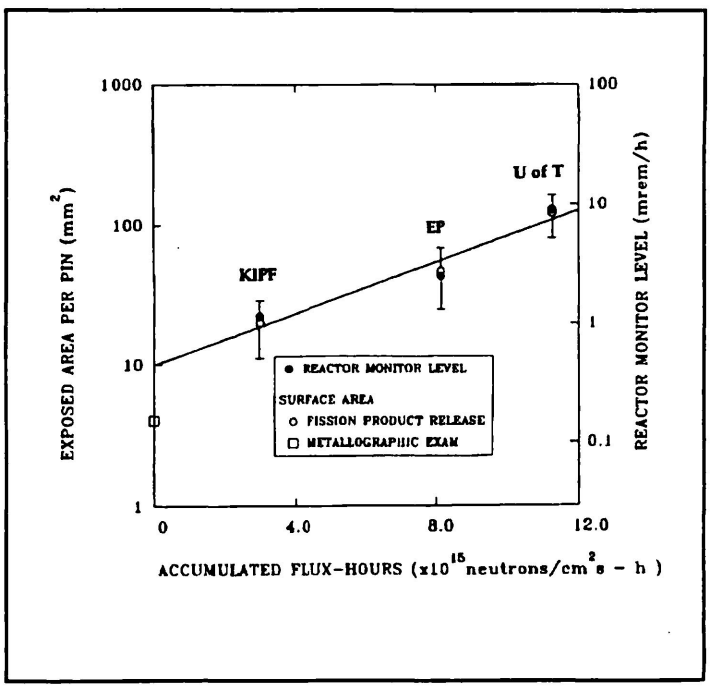

Figure 6

Increasing exposed fuel and alarm levels with burnup for U of T, EP and KIPF reactors.

The curve in Figure 6 also correlates well with the reactor alarm monitor levels given in Table 2 for the various reactors. Hence, the monitor levels serve as an indication of the "normal" progression of the fission product release and exposed fuel surface area.

The curve can be extrapolated back to zero burnup to determine the amount of fuel exposure for the unirradiated fuel pins. This implies that an average pin in Figure 1 would have ~10 mm^2 of fuel exposure. This value can be compared to a metallographic examination of archive fuel elements [20]. A band is seen at the end weld line of the fuel pin (Figure 7) after excess uranium-bearing material had been removed by machining. Based on the metallographic examination, the average exposed surface of each unirradiated fuel pin is estimated to be 4.0 mm^2 [20]. This value is in good agreement with that determined from the fission product release study (10 mm^2), i.e. the metallographic examination provides a lower-bound value since one must consider the total surface area rather than the geometrical area due to surface irregularities.

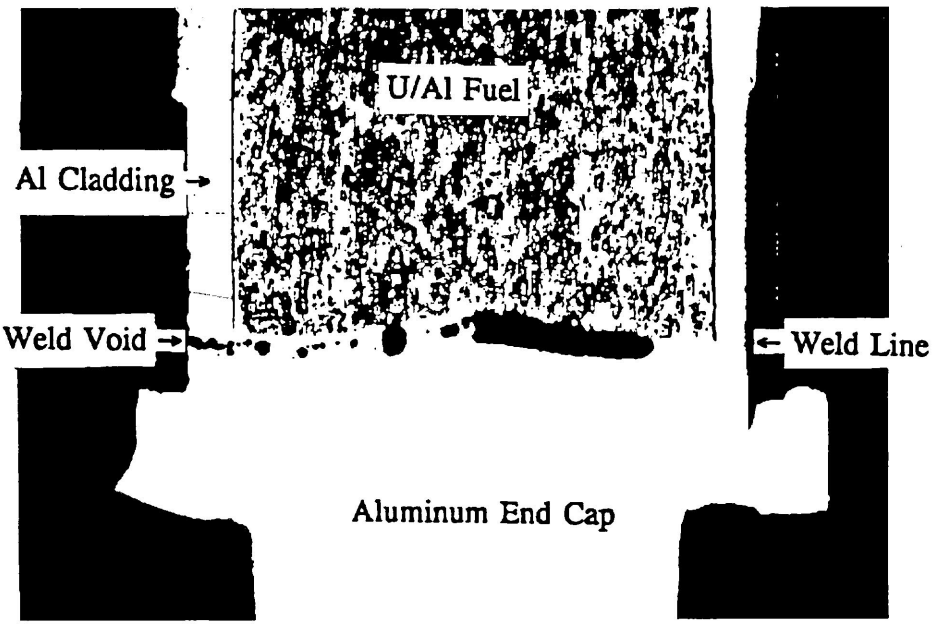

Figure 7

Metallographic examination of an archive HEU SLOWPOKE-2 fuel pin. (Courtesy of Atomic Energy of Canada Limited)

Since the activity of the short-lived fission products have been increasing with core burn-up, it is apparent that a larger surface area of uranium-bearing material is being exposed to the

coolant. For instance, corrosion at the contaminated end welds of the fuel pins may account for the increased release. The uniform corrosion rate of the aluminum cladding is sufficiently small (0.76 - 1.53 μm/yr at operating temperatures) that the cladding should remain intact throughout the core lifetime [20]. However, corrosion at the end-weld line could increase any surface irregularity thereby exposing more uranium-bearing material to the coolant. Unfortunately, limited data are available on the corrosion behaviour of uranium-aluminum alloys under conditions similar to those in the SLOWPOKE-2 reactor [14,21]. Aqueous corrosion of uranium-aluminum alloy fuel was observed in the Advanced Test Reactor (ATR) after the formation of a pit defect in the plate-type fuel; however, the coolant flow and temperature of the cladding of the ATR fuel were higher than those associated with the SLOWPOKE-2 reactor [21]. The corrosion rate of the uranium-aluminum alloy is expected to be about two to three times that of the aluminum cladding [20].

VISUAL EXAMINATION OF THE EP CORE

A visual examination of the high burnup SLOWPOKE-2 core at EP was performed on 24 September 1991. The core was lifted out of its resting position so that its entire length was exposed. A remote underwater television camera Westinghouse Model ETV 1250 with built-in light source and right-angle viewing attachment provided by Chalk River Laboratories (CRL), was lowered down beside the core. Direct observation of the entire outer ring of fuel pins and portions of some inner pins was possible.

This examination indicated that the core was in good condition with no evidence of gross failure, or any loss of structural integrity. The end welds of the fuel pins were visible with no significant evidence of corrosion (although the lighting and the resolution capability of the camera were limited). Some minor swelling was observed at the bottom section of ten to twelve peripheral fuel pins.

CONCLUSIONS

1. Highly enriched uranium (HEU) fuel elements for the SLOWPOKE-2 reactors have a band of uranium-bearing material (at the end-weld line) exposed to the coolant as a consequence of the fuel fabrication process. This band of exposed fuel is the initial source of fission products in the reactor container water.

2. Fission-product activity levels have been quantitatively measured by gamma spectroscopy methods in the reactor container water and gas headspace of SLOWPOKE-2 reactors fuelled with uranium alloy cores at the University of Toronto (U of T), Ecole Polytechnique (EP) and Kanata Isotope Production Facility (KIPF). Activity levels in the

SLOWPOKE-2 reactor at the Royal Military College (RMC) (containing a uranium dioxide core) have also been measured.

3. The predominant radionuclides observed in the reactor container water after approximately 100 hours of operation at 5 kW include: the noble gases; and the alkali metals, cesium and rubidium. These metals are produced principally from the decay of the noble gases. Iodine and molybdenum were also observed. Only noble gases are present in the gas headspace of the reactor container.

4. The release of the shorter-lived noble gases from the HEU alloy cores to the reactor container water is due predominantly to a recoil process. Increased activity levels with time may be attributed to corrosion of the end weld area. The exposed surface area predicted from the fission-product release study is consistent with the results of a metallographic examination of several unirradiated fuel pins.

5. The extremely low levels of fission products measured at the low enriched uranium (LEU) fuelled reactor at RMC are due to tramp uranium contamination on the surface of the Zircaloy cladding. In comparison, the ^{133}Xe levels were five orders of magnitude less than those measured at U of T.

6. The measured alarm monitor levels and fission-product activities correlate with the burnup of the various HEU reactors. The exposed fuel surface area has increased by an order of magnitude with burnup in the U of T core.

7. An underwater visual examination of the outer fuel elements of the EP core was performed. The core appeared to be in good condition with no evidence of gross deterioration, or any loss of structural integrity. No evidence of corrosion of the cladding was observed.

8. No fission products were detected in the pool water. In addition, the release of fission products into the reactor container water and gas headspace pose no immediate health or safety hazard.

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