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by James D. Heckelman and Konstanty Semenchuk

Lewis Research Center
Cleveland, Ohio

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AN IMPROVED DELAYED NEUTRON FISSION PRODUCT MONITOR*

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SUMMARY

An improved delayed neutron fission product monitor (FPM) has been developed at NASA's 60-megawatt (thermal) test reactor located at the Plum Brook Station near Sandusky, Ohio. Two neutron detectors (fission chambers) are used, and monitor the delayed neutrons at two different locations in the primary coolant system. The ratio (detector 1 count rate)/(detector 2 count rate) is used to indicate the presence of fission products.

During normal reactor operation when significant fission products are not present in the primary cooling water (PCW), the neutrons present at the detectors are from the decay of nitrogen-17. When fission products appear in the PCW, their half-lives are different from the half-life of N^{17}. The ratio will thus change, and the change may be uniquely related to the fission product activity in the PCW.

The activity of the fission product iodine-134 in the PCW of the Plum Brook Reactor (PBR) is routinely determined. Calculations provided the theoretical FPM ratios for assumed I^{134} levels. The theoretical curve was then verified by actual measurements taken during many reactor operating hours.

Calibration of the FPM system is easily accomplished by interchanging the detectors at one detector location, and adjusting the electronics so that the counting rates of both detector channels are equal.

The improved delayed neutron fission product monitor is in operation and has demonstrated reliable results.

INTRODUCTION

Fission products, the result of nuclear fission, are normally contained within the fuel elements of nuclear reactors by the fuel element cladding. A leak in the cladding of one or more fuel elements allows the fission products to be released into the primary coolant and is a potential hazard. Even a small leak must be detected because of the

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possibility of its becoming acute and causing severe radiation and system cleanup problems.

Various methods (ref. 1) are in use in nuclear reactor facilities to detect the presence of, and to measure the amount of, fission products in the primary coolant. One such system (ref. 2) performs this task by detecting and counting the number of the neutrons from the fission products present in the primary coolant. These neutrons, which are released from the daughter elements after fission has occurred, are called "delayed neutrons." Hence, such a system may be known as a "delayed neutron fission product monitor."

In a water-cooled reactor, neutrons are also produced in the PCW by the reactions (ref. 3)

$$\left.\begin{array}{c} O^{17}(n, p)N^{17*} \\ \text{and} \\ N^{17*} \xrightarrow[4.14\ \text{sec}]{\beta^-} O^{17} \xrightarrow[\text{instan}]{n} O^{16} \end{array}\right\} \qquad (1)$$

where * indicates the excited state, and are always present during reactor operation. A delayed neutron FPM must be capable of detecting the fission product neutrons in the presence of relatively large numbers of N^{17} neutrons. If two neutron measuring channels spaced a given distance apart in the PCW system are utilized, the ratio of the resultant N^{17} neutron activities at the two detectors does not respond to reactor power level changes. The two-detector system effectively increases the sensitivity of the FPM as a true indication of fission products in the PCW.

The PBR is a pressurized water cooled reactor with flow rates of approximately 18 000 gpm in the "main" cooling loop and 1300 gpm in the "shutdown" cooling loop. The core is composed of 27 aluminum clad U^{235} fuel elements of the MTR type, arranged in a 3×9 array. Twenty-two of the elements are stationary, and five are movable for control purposes. The development, theoretical performance, calibration, and actual performance of a two-detector delayed neutron FPM for this reactor is the subject of this report.

PERFORMANCE REQUIREMENTS FOR A FPM

A FPM for a nuclear reactor should:

(1) Be sensitive enough to alert the reactor operator to a significant leak of fission products into the PCW.

(2) Respond rapidly to the presence of fission products.

(3) Indicate the magnitude of the fission product inventory in the PCW and provide an alarm when the fission product inventory reaches a predetermined level.

(4) Indicate the trend of the fission product activity.

(5) Provide a permanent record of the fission product activity.

(6) Be reliable, stable, and require little maintenance.

(7) Be easily calibrated.

Because of the need at the PBR for a better FPM, the "two-detector delayed neutron fission product monitor" was developed.

SYSTEM DESCRIPTION

The principle of operation is based on neutron detection and the difference in half-lives of the fission products and the N^{17} produced during normal reactor operation in the PCW.

The system developed consists of two neutron detectors, hereafter referred to as detectors 1 and 2, placed a known distance apart on the reactor PCW pipes. Each detector is connected to a preamplifier, amplifier, base line discriminator, count rate meter (CRM) with log and linear voltage outputs, and appropriate power supplies. One pen of a two-pen indicating strip chart recorder displays the log count rate of either detectors 1 or 2 (switch selected). The second pen displays the voltage difference between the log

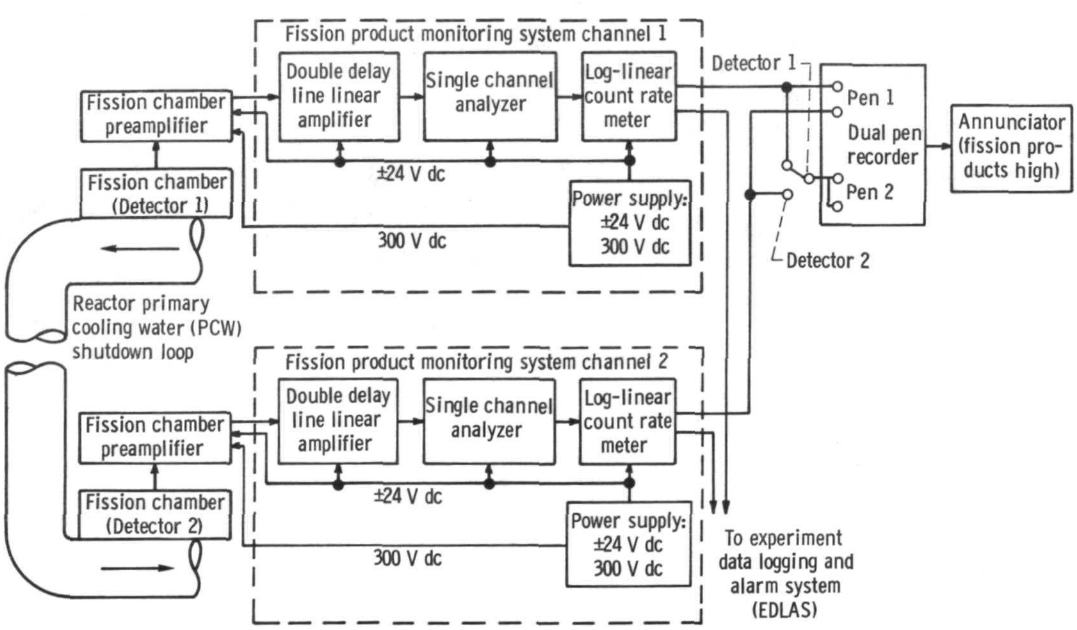

Figure 1. - Fission product monitoring system.

outputs of the CRM's (det. 1 - det. 2). This difference is the ratio (detector 1 count rate)/(detector 2 count rate). The linear outputs of the CRM's are connected to the facility Experiment Data Logging and Alarm System (EDLAS) that calculates the above ratio and displays it in digital form upon command. The purpose of the EDLAS tie-in is to obtain greater accuracy, when required. A block diagram of the system is shown in figure 1.

BASIS OF CALIBRATION FOR THE FISSION PRODUCT MONITOR

The Atomic Energy Commission license for the Plum Brook Reactor Facility (PBRF) limits the maximum amount of fission products permitted in the PCW by specifying limits on the activity of iodine-131 and strontium-90.

Because of its shorter half-life and higher activity, I^{134} activity in the PCW is measured routinely and used as the indicator for the I^{131} and Sr^{90} levels. Iodine-131 and strontium-90 levels are related to the I^{134} level by known relations, and their level is verified by analysis of samples taken at shutdown.

As discussed later in this report, the FPM developed essentially measures the neutron activity of the isotopes I^{137} and Br^{87} to indicate the fission product activity. Neutron emitters are I^{137} and Br^{87}. Iodine^{134}, that does not emit neutrons, is measured by laboratory techniques using a sample of water from the PCW system.

During the initial design calculations of the FPM, it was assumed that the ratio (detector 1 count rate)/(detector 2 count rate) could be uniquely related to the I^{134} activity in the PCW. The assumptions made for the theoretical performance of the FPM are:

(1) The fission product release from a leak in a fuel element consists of the normal (fission yield) distribution of six isotopes that emit delayed neutrons.

(2) There is no significant delay in the release of fission products from the leaking fuel element(s) into the PCW.

(3) The fission product activity in the PCW is proportional to the reactor power level.

(4) Equilibrium conditions exist for all isotopes of interest.

(5) The PCW flow is relatively constant.

Assuming the above, the FPM ratio will be independent of reactor power. The I^{134} level is proportional to reactor power. Thus, once the FPM ratio against I^{134} level relation is established for one power level, the I^{134} activity for any other power level can be easily determined from the indicated FPM ratio.

The theoretical relation of FPM ratio against I^{134} level in the PCW for the PBR was established for full power operation of 60 megawatts and a PCW flow rate of 1300 gpm in the shutdown loop. The results are presented in graphical form later in this report. The I^{134} activity for other reactor power levels and the same flow rate is found from the indicated FPM ratio by the equation:

$$I^{134}_{P(MW)} = I^{134}_{60(MW)} \frac{P(MW)}{60} \tag{2}$$

where

$I^{134}_{P(MW)}$ the unknown I^{134} activity at reactor power P, MW

$I^{134}_{60(MW)}$ the I^{134} activity for a given FPM ratio indication taken from the graph of FPM ratio against I^{134} activity

P reactor power, MW

The theoretical graph of FPM ratio against I^{134} activity was verified by taking data for many reactor operating hours and plotting the actual (measured) values on the graph. The theoretical calculations and the calibrating techniques used are explained in greater detail in later section of this report.

CONSIDERATIONS IN CHOOSING THE LOCATIONS OF THE FPM DETECTORS IN THE PRIMARY COOLING WATER SYSTEM

The placement of the detectors considered the following items:

(1) The time necessary for a particle to travel from detectors 1 to 2

(2) The time necessary for a particle to travel from the reactor core to detector 1

(3) The type of fission product leak in the fuel element(s) and its effect on the FPM ratio

(4) The geometry of the detectors relative to the neutron source

(5) The interchangeability of the detectors and their associated electronic channels for the purpose of calibrating the system

(6) The changes in the PCW flow rate and the resulting effect on the FPM ratio

The significance of these items will now be discussed.

Location of the Detectors Relative to Each Other and Relative to the Reactor Core

The principle of operation of the FPM described in this report is, as previously noted, the difference in half-lives between the N^{17} present in the PCW at all times and the fission products. When fission products are not present, the only isotope existing in the PCW that emits neutrons is N^{17}. This isotope decays with a 4.14-second half-life. With fission products, there are six isotopes that produce delayed neutrons (refs. 4 and 5), that are listed in table I. The half-lives of the isotopes under study then range from 0.05 to 55.6 seconds. The detector locations are chosen by considering the availability of each isotope and the resultant neutron activity at each detector for all possible detector positions.

TABLE I. - DELAYED NEUTRON

EMITTERS (REFS. 4 AND 5)

Isotope	Half-life, sec	Fraction of fission neutrons delayed
1	0.05	0.00025
2	.43	.00085
3	1.52	.00241
4	4.51	.00213
5 (I^{137})	22.0	.00166
6 (Br^{87})	55.6	.00025

The following points lead to the choice of location for detector 1 at the PBRF.

(1) The fission products are produced only in or very near to the reactor core. The detectors of the FPM must respond only to the delayed neutrons, and cannot be placed so near the reactor core that they may be in the prompt neutron field. This limits the location of the first detector so that the minimum time required for a particle to travel from the core to detector 1 is in the order of 10 seconds. Thus, the isotopes with the 0.05- to 1.52-seconds half-lives will have decayed to an insignificant level.

(2) If a comparison is made of the fraction of fission neutrons delayed from each isotope shown in table I, one notices that the isotopes with the shortest and longest half-lives contribute the fewest number of delayed neutrons.

(3) A break in the fuel element cladding may sometimes be of such a nature that the isotopes in question are delayed in reaching the PCW. It is postulated that delays of up to several seconds could occur if the release were in "bursts" (caused by pressure buildup) several seconds apart, or if the time for the atoms of the fission products to migrate through a very small opening in the fuel element cladding were in the order of several seconds. Therefore, the short half-lived isotopes should not be used to detect the presence of fission products in the PCW since the variance would severely affect the calibration of the system.

(4) Isotope number four adds little to the change in the ratio due to the presence of fission products since its half-life is very nearly the same as the N^{17} half-life.

(5) The detectors must be far enough from the core so that the N^{17} has decayed to a

level that will not mask the fission product isotopes when they appear in small amounts. Also, the detectors must not be so far from the core that the number of neutrons available from the N^{17} and the fission products would provide poor counting statistics.

With these five points in mind, the location for the first detector is chosen such that the time for a particle to travel from the core to detector 1 is in the order of 15 to 20 seconds. Only two isotopes will thus be significant in causing the change in ratio when fission products appear in the PCW. These isotopes are I^{137} and Br^{87}, with half-lives of 22.0 and 55.6 seconds, respectively.

The following points lead to the choice of location for detector 2 relative to detector 1:

(1) The ratio approaches one as the fission product inventory increases.

(2) If the time required for a particle to travel from detector 1 to 2 is short, say in the order of 1 second, the count rate of detector 2 will be nearly the same as the count rate of detector 1 even when fission products are present.

(3) If the time required for a particle to travel from detector 1 to 2 is long, say in the order of 16 seconds, the count rate of detector 2 may be too low to be useful since the variance in the count rate would be a large percentage of the nominal value (variance = $\sqrt{\text{count rate}}$).

With these three points in mind, the location of detector 1 relative to detector 2 is chosen such that the time for a particle to travel from detector 1 to 2 is in the order of 6 to 8 seconds. Then the ratio during normal reactor operation when fission products are not present would be three or four.

Detector Geometry

The absolute counting rate of each channel is not important since the ratio of the two channels is used to indicate the presence of fission products. However, the counting rate must be great enough so that the variance in counting rate is a reasonable value, as previously noted. At the PBR, an acceptable counting rate was achieved by positioning a 2-inch diameter, 8-inch long fission chamber next to the PCW shutdown loop pipe. The pipe is stainless steel and 8 inches in diameter. The resultant counting rates are approximately 300 cps at detector 1 and 100 cps at detector 2 at a reactor power level of 60 megawatts. The above counting rates are considered to be the lower limit since the variance becomes significant at lower values.

Interchangeability of Detectors

Calibration of the FPM system is accomplished, in part, by placing detector 2 in detector 1 position as described later in this report. The purpose of this is to bring the two channels to exactly the same sensitivity (i.e., the same count rate for a given $N/(cm^2)(sec)$. To enable the detectors to be interchanged, a holder was strapped to the PCW pipes. Because of the rather large attenuation of the neutrons through the stainless steel pipe and because of the closeness of the fission chamber to the source, the detector holders must always position the fission chambers within 1/16 inch or less of the nominal distance each time they are replaced in the holders. A further complication is that the operation may have to be performed remotely. This is the case at PBR since the PCW shutdown loop is under approximately 20 feet of water. The fission chamber and preamplifier are protected from their environment by enclosing them in an aluminum container which is pressurized with helium to prevent water from entering in the event of a small leak. Thus, in addition, the package may become rather clumsy. All of the above must be taken into consideration when designing the detector holders.

Changes in the PCW Flow and the Effects on the FPM Ratio

The last consideration to be discussed concerning the placement of the detectors is the possible changes in the PCW flow rate past the detectors. As the flow increases, the time for a particle to travel from the core to detector 1 and from detector 1 to 2 decreases. This will decrease the ratio. The opposite is, of course, true for a decrease in flow rate. Thus, the detectors should be located in the primary coolant system so that the flow from the reactor core to the first and second detectors can be maintained constant. This can be accomplished either by a manual adjustment (valve) or by automatic means (servovalve with feedback from a flow measuring device).

At the PBR, the flow rate in the PCW system could not be maintained as constant as desired for the system. It was, therefore, necessary to establish the relation for the FPM ratio against I^{134} activity for several flow rates. Interpolation between the assumed flow rates is easily performed on the graph. These graphs are presented in later sections of this report.

CALCULATIONS AND THEORETICAL PERFORMANCE

Because there is no acceptable direct means to vary the fission product inventory in the PCW, rather extensive and accurate calculations were performed to determine the theoretical performance of the FPM system. The curve generated from these calculations then sufficed until sufficient data was obtained to verify the operation of the system. Therefore, the information necessary to make the calculations was carefully and accurately assembled from drawings, field measurements, and in some cases, special tests.

The following calculations were made.

(1) The time required for a particle to travel from the core centerline to detector 1 and to 2 for several expected values of PCW flow rate.

(2) The N^{17} neutron activity at detector 1 and 2 for full reactor power, and the resultant FPM ratio for each PCW flow rate assumed in (1).

(3) The fission product delayed neutron activities at detectors 1 and 2 equivalent to a range of equilibrium I^{134} activities, and the resultant FPM ratios for each PCW flow rate assumed in (1).

The nominal flow rate for the PBR shutdown loop is 1300 gpm, and the nominal full power is 60 megawatts. The range of equilibrium I^{134} activities in the PCW considered is 0 to 40 000 d/(min)(ml). Examples of these calculations for the PBR FPM will now be illustrated.

(1) The calculation of times required for a particle to travel from the core centerline to each detector for a flow rate of 1300 gpm is shown.

Time delay inside the core and reactor vessel. Empirically determined to be

$$t_1 = 12.9 \text{ sec} \tag{3}$$

Time from the outlet of the reactor vessel to the first detector.

Pipe, 17 ft of 8-in. diam; 17 ft × 2.61 gal/ft, gal	44.4
Heat exchanger, gal	40.0
Total, gal	84.4

Then the time from the outlet of the reactor vessel to the first detector is

$$t_2 = \frac{84.4 \text{ gal} \times 60 \text{ sec/min}}{1300 \text{ gal/min}} = 3.9 \text{ sec} \tag{4}$$

Time between detectors 1 and 2.

Pipe with flow of 1300 gpm, 30.25 ft of 8-in. diam; 30.25 ft × 2.61 gal/ft, gal	79.0
Pipe with flow of 1300 gpm, 17.8 ft of 6-in. diam; 17.8 ft × 1.47 gal/ft, gal	26.1
Total volume at 1300 gpm, gal	105.1
Pipe with flow of 925 gpm,[1] 11.0 ft of 8-in. diam; 11 ft × 2.61 gal/ft, gal	28.7

[1]The 925 gpm is the flow at detector 2. The 1300 gpm is the total flow in the shutdown loop, 375 gpm of which is diverted for experiment test hole cooling 11 feet upstream of detector 2.

So, the time between detectors is

$$\Delta t_{3-4} = \frac{105.1 \text{ gal} \times 60 \text{ sec/min}}{1300 \text{ gal/min}} + \frac{28.7 \text{ gal} \times 60 \text{ sec/min}}{925 \text{ gal/min}}$$

$$= 4.8 \text{ sec} + 1.9 \text{ sec} = 6.7 \text{ sec} \tag{5}$$

Therefore,

Time from the core centerline to detector 1.

$$t_3 = 12.9 \text{ sec} + 3.9 \text{ sec} = 16.8 \text{ sec} \tag{6}$$

and

Time from the core centerline to detector 2.

$$t_4 = 12.9 \text{ sec} + 3.9 \text{ sec} + 6.7 \text{ sec} = 23.5 \text{ sec} \tag{7}$$

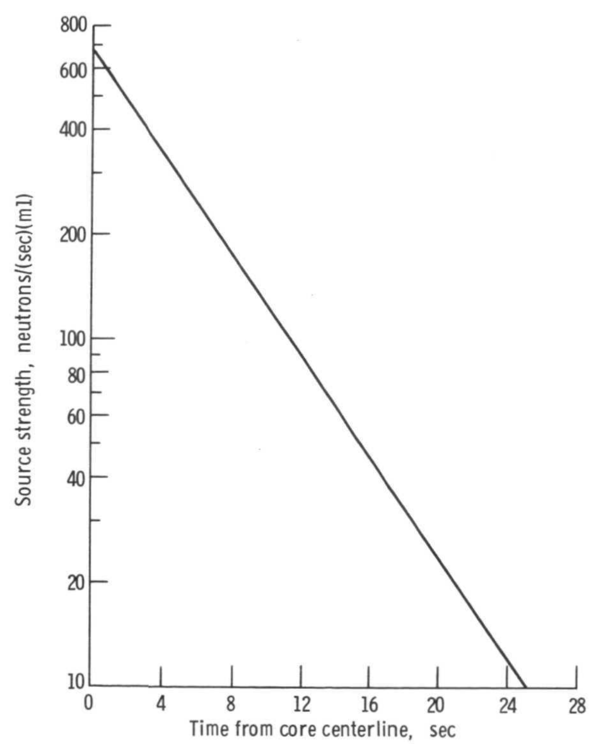

Figure 2. - Nitrogen-17 neutron activity of water leaving reactor core centerline. Reactor power, 60 megawatts.

(2) Figure 2 is a decay curve of N^{17}. From this figure, the neutron activity due to N^{17} alone at detector 1 (16.8 sec from core) is 2400 d/(min)(ml), and at detector 2 (23.5 sec from core) is 780 d/(min)(ml). The ratio R_o of the two activities due to N^{17} only is

$$R_o = \frac{n_1(N^{17})}{n_2(N^{17})} = \frac{2400}{780} = 3.08 \tag{8}$$

(3) If a fuel leak occurs, there are six isotopes that produce delayed fission neutrons (refs. 4 and 5). These are listed in table I in an earlier section of this report. The first three isotopes have very short half-lives and are almost completely decayed by the time they reach the first detector. So, only isotopes 4 to 6 contribute to the neutron activities at the detectors. The delayed neutron activity at detectors 1 and 2 is calculated as follows:

The yields (ref. 6) of I^{134} and I^{137} are 7.8 and 4.5 percent, respectively. Then the total activity (n and β) of I^{137} at a given total activity (γ and β) of I^{134} is

$$\text{Total activity } (I^{137}) = \frac{4.5}{7.8} \times \text{total activity } (I^{134}) \tag{9}$$

The I^{137} isotope contributes neutrons (ref. 6) equal to 3 percent of its total activity. Thus, the neutron activity contributed by I^{137} is

$$n(I^{137}) = \left(\frac{4.5}{7.8}\right)(0.03) \times \text{total activity } (I^{134})$$

$$= 0.0184 \times \text{total activity } (I^{134}) \tag{10}$$

From table I, the neutron activity contribution of each isotope is calculated in the following manner.

$$\text{Isotope 1 neutron yield} = \frac{25}{166} n(I^{137}) = 0.00278 \times \text{total activity } (I^{134})$$

$$\text{Isotope 2 neutron yield} = \frac{85}{166} n(I^{137}) = 0.00943 \times \text{total activity } (I^{134})$$

$$\text{Isotope 3 neutron yield} = \frac{241}{166} n(I^{137}) = 0.0267 \times \text{total activity } (I^{134})$$

$$\text{Isotope 4 neutron yield} = \frac{213}{166}\, n(I^{137}) = 0.0236 \times \text{total activity } (I^{134})$$

$$\text{Isotope 5 neutron yield} = \frac{166}{166}\, n(I^{137}) = 0.0184 \times \text{total activity } (I^{134})$$

$$\text{Isotope 6 neutron yield} = \frac{25}{166}\, n(I^{137}) = 0.00278 \times \text{total activity } (I^{134})$$

These delayed neutrons are produced at the reactor core centerline. The neutron levels at the detectors are determined by the half-lives of the isotopes. For instance, the half-life of the isotope 5 (I^{137}) is 22 seconds, and the time from the core to the first detector for a flow of 1300 gpm was calculated to be 16.8 seconds. Then the I^{137} neutron activity at detector 1 is

$$n_1(I^{137}) = \left(\frac{1}{2}\right)^{nh} n(I^{137}) = \left(\frac{1}{2}\right)^{16.8/22} n(I^{137}) \tag{11}$$

where

$n(I^{137})$	I^{137} neutron activity at birth
$n_1(I^{137})$	I^{137} neutron activity at detector 1
nh	number of half-lives from birth

Likewise, the I^{137} neutron activity at detector 2 is

$$n_2(I^{137}) = \left(\frac{1}{2}\right)^{23.5/22} n(I^{137}) \tag{12}$$

A similar equation was derived for isotopes 4 and 6, but will not be presented here.

The neutron activity at the detectors due to isotopes 4 to 6 was calculated for I^{134} equilibrium activities from 5000 to 40 000 d/(min)(ml). The results are tabulated in table II for a PCW flow rate of 1300 gpm.

TABLE II. - DELAYED NEUTRON ACTIVITIES FOR GIVEN I^{134} EQUILIBRIUM ACTIVITY LEVELS IN PRIMARY COOLING WATER SHUTDOWN LOOP AT 1300 GALLONS PER MINUTE

I^{134} d/(min)(ml)	Fission product neutron activities, n/(min)(ml)										
	At birth, n			At detector 1, n_1			Total	At detector 2, n_2			Total
	Isotope							Isotope			
	4	5	6	4	5	6		4	5	6	
5 000	118	92	14	9	54	11	74	3	45	10	58
10 000	236	184	28	18	108	23	149	7	89	21	117
15 000	354	276	42	27	163	34	224	10	134	31	175
20 000	472	368	56	35	217	45	297	14	178	42	234
25 000	590	460	70	44	271	57	372	17	222	53	292
30 000	708	552	84	53	325	68	446	21	267	63	351
35 000	826	664	98	62	379	79	520	24	311	73	408
40 000	944	736	112	71	434	91	596	27	356	84	467

The ratio R is defined as the total neutron activity at detector 1 divided by the total neutron activity at detector 2. That is,

$$R = \frac{n_1(N^{17}) + n_1(\text{isotopes 4 to 6})}{n_2(N^{17}) + n_2(\text{isotopes 4 to 6})} \tag{13}$$

where

$n_1(N^{17})$ neutron activity due to N^{17} at detector 1

$n_2(N^{17})$ neutron activity due to N^{17} at detector 2

n_1(isotopes 4 to 6) neutron activity due to fission products at detector 1

n_2(isotopes 4 to 6) neutron activity due to fission products at detector 2

From the above, the FPM ratio can be calculated and plotted against I^{134} equilibrium activities from 0 to 40 000 d/(min)(ml). The result is the graph presented in figure 3. Note that the results for flow rates other than 1300 gpm are also plotted on this same graph, and that interpolation for other flow rates is easily accomplished.

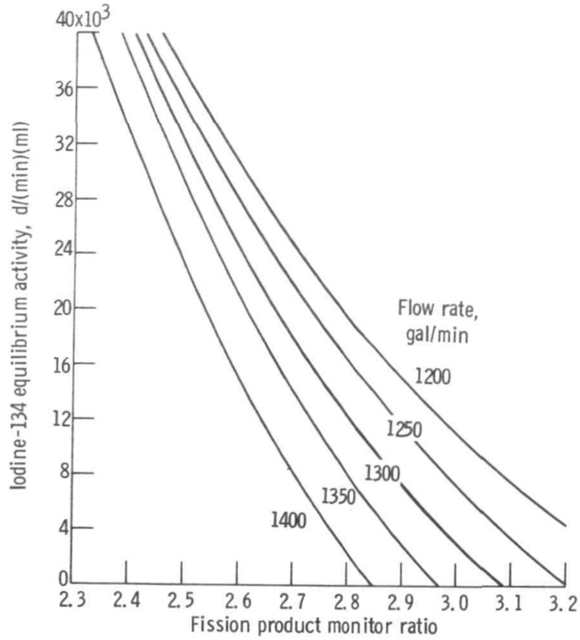

Figure 3. - Fission product monitor ratio against iodine-134 activity (theoretical). Reactor power, 60 megawatts.

CALIBRATION METHODS FOR THE FISSION PRODUCT MONITOR

Calibration of the Electronics

The calibration of the counting system is relatively easy and straightforward. The calibration is performed while the reactor is operating at a constant power level and uses the isotopes present in the PCW as the neutron sources. The generalized procedure is as follows:

(1) A discriminator curve (cps against discriminator settings) is run for each channel. A tentative operating point which provides the proper discrimination of the (n, α) and (n, γ) reactions and noise for each channel is then chosen.

(2) The counting rate of detector 1 is carefully noted by connecting a scaler to the discriminator output. The counts should be taken for at least 5 minutes to obtain an accurate average.

(3) Detector 1 is then removed from its holder and detector 2 put in its place.

(4) The discriminator for detector 2 is then adjusted so that its average counting rate is exactly the same as detector 1.

(5) The detectors are then placed back in their respective locations.

Since (1) the efficiency of the detectors is nearly the same, (2) the channels are nearly the same electronically, (3) the geometry of the two detectors is the same relative to the neutron source, and (4) the counting rates of both detectors have been made equal, the true ratio will be indicated when the detectors are replaced in their normal positions.

Calibration of the FPM Ratio Against I^{134} Activity in the PCW

The theoretical curves of FPM ratio against I^{134} equilibrium activity (fig. 3) were verified as follows. A sample of PCW was taken and laboratory techniques used to determine the I^{134} activity of the PCW at the time the sample was taken. As the PCW sample was taken, the average FPM ratio and the PCW flow rate were noted. This process was continued until sufficient data had been obtained to define a curve of FPM ratio against I^{134} level.

CALIBRATION RESULTS FOR THE FISSION PRODUCT MONITOR

Comparison of the Theoretical and the Measured Curves

The calibration data obtained was normalized to a PCW flow rate of 1300 gpm and plotted. The resultant curve is shown in figure 4. The measured quantities, when plotted, agreed with the theoretical curve for a PCW flow of 1300 gpm. It is, therefore, assumed that the theoretical curves for the other flow rates are also correct and may be used with confidence.

Variance in the FPM System

The laboratory method for determining the I^{134} content in the PCW has a variance of ±30 percent at the 95 percent confidence level for I^{134} activities >10 000 d/(min)(ml). The variance in the FPM ratio indication is ±5 percent at the 95 percent confidence level for ratios equivalent to I^{134} activities >10 000 d/(min)(ml). This variance in ratio results in a variance of the I^{134} (from the graph) of ±40 percent. The total variance (or uncertainty) at the 95 percent confidence level in knowing the I^{134} activity in the PCW as indicated by the FPM for I^{134} activities >10 000 d/(min)(ml) is then:

$$2\sigma = \sqrt{(30)^2 + (40)^2} = \pm 50 \text{ percent} \tag{14}$$

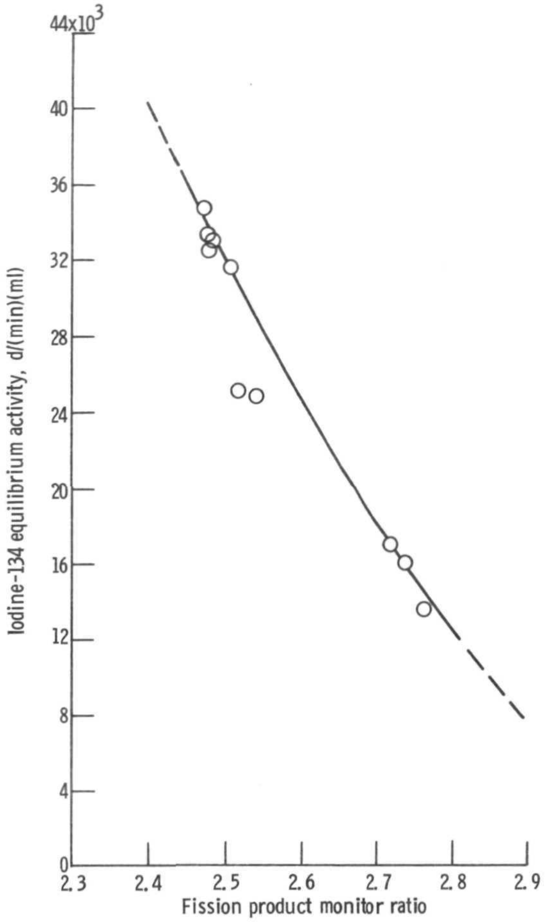

Figure 4. - Fission product monitor ratio against iodine-134 activity (measured). Reactor power, 60 megawatts; flow rate, 1300 gallons per minute.

OPERATING EXPERIENCE WITH THE FISSION PRODUCT MONITOR

Accuracy

As previously noted in this report, I^{134} equilibrium activity in the PCW is routinely determined by laboratory techniques at the PBR as an indicator of fission products. The sampling is performed once every day. There are, therefore, frequent occasions to compare the I^{134} activity as indicated by the FPM with the true value. Thus far, the correlation has been excellent.

One of the assumptions made in the initial design of the FPM is that the release of the fission products into the PCW is instantaneous. Since the correlation noted above has been excellent, this assumption as well as the other assumptions listed in an earlier section of this report appear to be valid a great percentage of the time. It is credible, however, that the release of fission products in the PCW may not be instantaneous; that there may be a significant delay (several minutes or more) in the release of fission products and, in effect, "old" fission products which do not yield delayed neutrons could be released (i.e., isotopes I^{137} and Br^{87} would be decayed to lower than normal or insignificant activities). In such a case, the FPM would not accurately indicate the true fission product activity. This type of leak, as yet, has not been experienced to any great degree (if at all) at the PBR.

Sensitivity

The FPM is usable in the detection of fission products in the PCW which have an equivalent I^{134} equilibrium activity as low as 5000 d/(min)(ml).

Response

The response of the FPM is in the order of 120 seconds (one time constant). The theoretical response is approximately 25 seconds. This is the time required for a particle to travel from the core centerline to detector 2. The additional response time is required in the damping of the electronics so that an average counting rate with low variance is obtained.

The above response time is very adequate and predicts what the I^{134} activity will be when equilibrium (for the I^{134}) is achieved in approximately 5 hours if the leak continues at the same rate.

The nearly instantaneous response of the FPM is perhaps the greatest utility of the system, since the information is immediately utilized in making the decision to terminate or to continue reactor operations.

Proposed Improvements of the Fission Product Monitor

The two-detector delayed neutron fission product monitor accurately indicates the I^{134} equilibrium activity in the PCW, and has proven to be a valuable tool in reactor operations at PBR. Operating experience, however, has indicated that several additional improvements can be made. These improvements probably will be made to the existing FPM at PBRF, and are noted here so that they can be incorporated in any future design.

It is desirable to reduce the variance in the ratio. Factors which affect the variance are:

(1) Variance in the counting rate

(2) Variance in the time for a particle to travel from the core to each detector, caused by changes in the flow rate

(3) Variance in the detector location (geometry) due to vibration and mounting technique

The variance in counting rate can be reduced by improving the geometry of the fission chambers relative to the neutron source. The variance in transit times for the isotopes can be reduced by moving the detectors from the PCW shutdown system pipes to a separate regulated flow system. The variance in fission chamber mounting can be decreased by improving the holder to provide more exact positioning. It is also desirable to increase the change in ratio for a given change in the I^{134} level.

All of the above can be easily accomplished by the design concept shown in figure 5. The volume of the tank in which the detectors are placed is approximately $1\frac{1}{2}$ gallons.

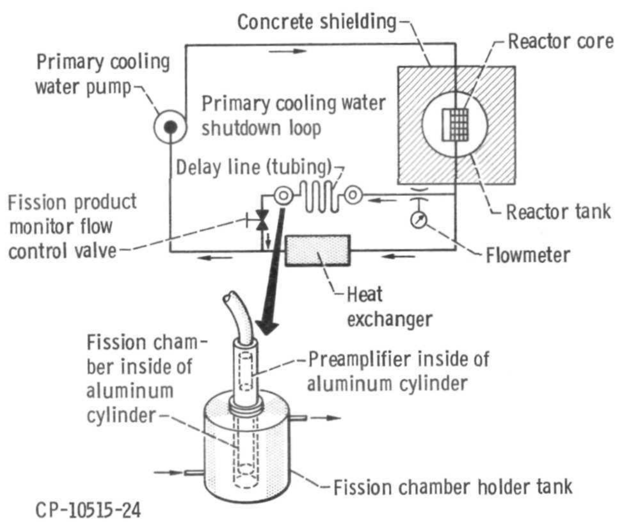

Figure 5. - Proposed fission product monitor system flow loop and chamber mounting.

Baffles are used in each tank to insure that the flow path is uniform in the tank annulus. The design flow rate is 20 gpm, but can be varied to achieve the desired ratio due to N^{17} only. The design time for a particle to travel between detectors is 8.0 seconds, and the design time for a particle to travel from the core to detector 1 is 20.0 seconds.

The system still will be somewhat affected by a change in the PCW flow rate, but only when fission products are present. Also, the effect will be greatly reduced, as is shown in figure 6. The effect could be eliminated completely only if the primary coolant for the FPM loop could be taken directly from the reactor core rather than several feet

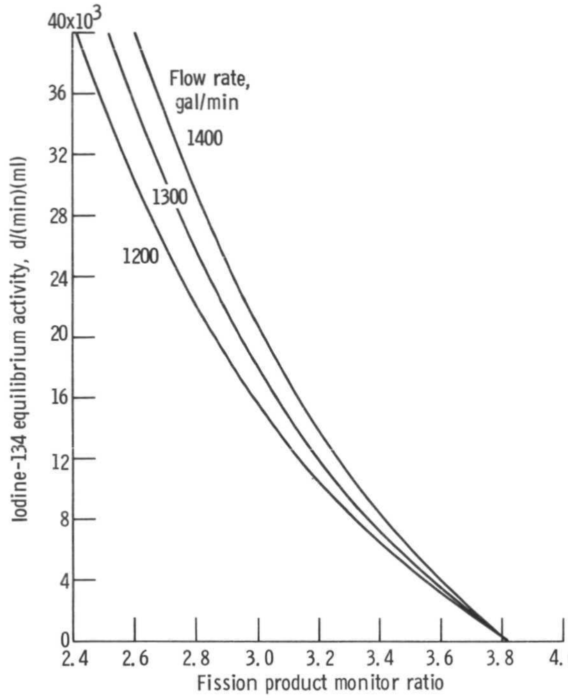

Figure 6. - Fission product monitor ratio against iodine-134 activity (theoretical). Time to first detector at 1300 gallons per minute, 20 seconds; time between detectors, 8.0 seconds.

downstream of the core. However, this is not practical at the PBR.

The proposed changes should make the system more sensitive to changes in the I^{134} level in the PCW. For instance, an increase of the I^{134} level from 0 to 40 000 d/(min)(ml) at a flow rate of 1300 gpm will cause a ratio change of 1.4 compared to a change of only 0.6 in the present system.

Removal and replacement of the detectors in the tanks should be easy since the tank can be placed in a more convenient location closer to the surface of the shielding water.

Finally, the counting rate of the proposed system should increase by a factor of approximately 3 because of: (1) the improved geometry, and (2) the lower absorption of the thermal neutrons by the material separating the detectors and the PCW.

CONCLUSIONS

The two-detector FPM system has been in operation at the PBR for about 1 year. The initial calibration, started about 1 year ago, took approximately 6 months.

The FPM performs well and meets the design criteria stated at the beginning of this report. The system, mainly because of its near instantaneous response and accuracy, has significantly aided reactor operations, especially during a fission product leak.

Operating experience has indicated certain improvements can be made to further improve the performance of the FPM, and were noted in this report. These improvements are being implemented at the PBR.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 6, 1969,
120-27.

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