COMPARISON OF MEASURED AND PREDICTED SENSITIVITIES OF IN-CORE FLUX DETECTORS

D.P. McALLINDON

AECL, Chalk River Laboratories, Chalk River, ON K0J 1J0

ABSTRACT

In-core flux detectors (ICFDs), also known as self-powered neutron detectors, are key elements in CANDU ® reactor control and safety. One of the key performance characteristics of ICFDs is their sensitivity ,which changes with burnup of the current-producing materials in the detector. Sensitivity measurements on thirteen Straight Individually Replaceable (SIR) ICFDs that were irradiated in NRU for over 10 years showed some significant discrepancies with the predictions. As well, a study of the change of sensitivity of platinum-coiled detectors from Bruce A and Pickering B shows that these detectors are not burning up as fast as expected. is*

1. INTRODUCTION

In-core flux detectors (ICFDs), also known as self-powered neutron detectors, are key elements in CANDU reactor control and safety. One of the key performance characteristics of ICFDs is their sensitivity. The sensitivity of a detector changes with burnup of the current-producing materials in the detector. Burnup is a direct consequence of irradiation in a neutron flux. Predictions for the change in sensitivity of the detectors with total irradiation (burnup curves) were made using theoretical predictions of sensitivity, based on a detailed model of the detector interactions with neutron and gamma flux (ICARES) combined with fits of experimental measurements to determine some constants that were not calculable using ICARES.[1,2,3,4]

Thirteen prototype Straight Individually Replaceable (SIR) ICFDs of various types (vanadium, Inconel, and platinum-clad Inconel) have been irradiated in the NRU core since 1981. Further measurements of the sensitivity of these detectors were done in 1995 January and 1995 November using a Travelling Flux Detector (TFD). These measurements are combined with earlier reported measurements to compare the long-term changes in sensitivity to the predicted changes. This is the first time that long-term changes in sensitivity have been compared with the theoretical predictions.

Although the predicted burnup curve for vanadium detectors matched the measured burnup curve quite well, discrepancies were found between the measurements and predictions for the burnup curves of platinum-clad Inconel and Inconel detectors. For these detectors, a breeding factor caused by Nickel-59 was expected to increase the detector sensitivity for the first four years of irradiation after which the sensitivity was expected to decrease. Experimental observations are that the sensitivity of these detectors did increase as expected over the first four years but has continued to increase or has stayed the same. The predicted decrease has not occurred.

In addition to the NRU data, current measurements from insulation resistance data were used to trend the sensitivity of platinum coiled detectors in Pickering B Unit 5 and Bruce A Units 3 and 4. As with the platinum-clad Inconel and Inconel SIR detectors in NRU, these detectors are not burning out as quickly as predicted. Various theories to explain the discrepancy between measured and predicted burnup curves are put forward.

---

* CANDU® is a registered trademark of Atomic Energy of Canada Limited (AECL).

The comparison of burnup curves for the various types of detectors and the progress in investigating theories as to why discrepancies exist are reviewed.

2. REVIEW OF THEORY OF OPERATION OF ICFDS

In-core flux detectors consist of a metallic central emitter separated from an outer metallic sheath (the collector) by a layer of oxide insulation (Figure 1). In a neutron and gamma flux, electrons are ejected from the emitter, generating a positive charge on the emitter with respect to the collector. When the emitter and collector are connected through an external circuit, a current is produced in that circuit. The magnitude of the current is related to the neutron and gamma flux.

In general, there are three nuclear interactions that can result in an electron being ejected from a material. These nuclear interactions can occur in the emitter, collector, or insulator (Figure 2). Depending on where an electron is ejected from and deposited, a net positive charge, net negative charge, or no net charge is produced. The probability of the interactions depends on the neutron and gamma cross-sections, density, and atomic number of the material, the energy spectrum of the neutron and gamma flux, and detector geometry. These interactions are discussed briefly below. Refer to Reference 5 for further information.

> (n, β) - An atom absorbs a neutron, becomes unstable and decays with a characteristic half-life by the emission of an energetic electron or beta particle. As a result of this process, the original atom transmutes into an element with a higher atomic number and atomic mass. This mechanism results in the production of current with a half-life characteristic of the unstable isotope. Vanadium, rhodium, and manganese are examples of elements that produce current by the (n, β) process.
>
> (n, γ, e) - The absorption of a neutron by an atom results in the immediate emission of capture gamma rays. The original atom transmutes into a new isotope of the atom by the neutron capture. The gamma rays *produced* can then interact with matter by Compton scattering, the photoelectric effect, or pair production. The (n, γ, e) mechanism produces current almost instantaneously in response to neutron flux and is therefore referred to as a "prompt" interaction.
>
> (γ, e) - The (n, γ, e) interaction dealt with the specific case of electrons produced by gamma rays resulting from neutron capture. External reactor gamma rays can also eject electrons through the (γ, e) interaction. The probability of this interaction depends on the flux and energy of the external gamma rays, and the atomic number and density of the matter with which they interact. No transmutation of atoms occurs in the (γ, e) interaction. The (γ, e) mechanism produces current promptly in response to gamma flux; however, the gamma flux is itself composed of prompt and delayed fractions. In a generic CANDU core, about 70% of gamma flux is prompt.

An ideal detector would be one that has only a single charge-producing mechanism in the emitter so that its behaviour could be easily predicted. In practice, all three charge-producing interactions occur in the materials and impurities of both the collector and the emitter; consequently, the resulting current is a complex result that changes with irradiation, local neutron/gamma flux ratio, and energy spectra.

An equivalent electrical circuit of an ICFD is shown in Figure 3. A detector is modelled as a current source with a parallel resistance representing the cable insulation. The measurement circuit may consist of an ammeter to measure current directly (as shown in Figure 3), a load resistor across which the voltage is measured to obtain the current, or a current-to-voltage amplifier.

Detector current is the sum of the current produced by each mechanism, that is,

$$I = I(n, \gamma, e) + I(n, \beta) + I(\gamma, e) \qquad (2.1)$$

The relative contributions of each mechanism to the total current for the four types of detectors used in this study are shown in Table 1. These data were obtained from experimental measurement and do not necessarily add up to 100%. A negative contribution implies electron transfer from the collector to the emitter. As well, Table 2 gives the typical initial sensitivity of each type of detector.

3. PREDICTIONS OF BURNUP OF ICFDS

The predictions of burnup are based on an understanding of the current mechanisms in each type of detector. An equation is derived based on the current mechanisms, and the constants of the equation are calculated by ICARES, where possible. Remaining constants are determined by fitting to experimental results using a least squares method.

The form of the equation fitted is

$$\frac{S(\phi)}{S(0)} = \frac{A(\phi) + kB(\phi) + G}{S(0)} \qquad (3.1)$$

where

S is the sensitivity of the detector,
A(ϕ) is a known term using values from ICARES and is explained below for each type of detector,
B(ϕ) is the known equation for burn-in of ^{59}Ni,
k is an unknown rate constant for the burn-in of ^{59}Ni,
G is the unknown gamma sensitivity, and
f is the fluence.

G and k are determined by the fit.

The burn-in of ^{59}Ni can be expressed as

$$B(\phi) = \frac{\sigma_{58}}{\sigma_{59} - \sigma_{58}}(e^{-\sigma_{58}\phi} - e^{-\sigma_{59}\phi}) \qquad (3.2)$$

where

σ_{58} is the neutron capture cross-section of ^{59}Ni, and
σ_{59} is the neutron capture cross-section of ^{59}Ni.

The following sections describe the equations used to predict the burnup in each type of detector. The proportion of the main contributors to current can be seen from Table 1.

3.1 Inconel Detector Burnup

Inconel contributes current in all types of detectors because it is present at least in the sheath; therefore, the Inconel detector will be discussed first.

Current in the Inconel detectors is mainly due to the following mechanisms:

1. (n, γ,e) in the Inconel of the emitter,
2. (n, γ,e) in ^{59}Ni, an isotope not present in the initial Inconel that burns in and has a large neutron capture cross-section (kB(ϕ) in Equation 3.1), and
3. (γ,e) in the Inconel of the emitter from external gamma rays(G in Equation 3.1).

For Inconel detectors,

$$A(\phi) = S(n,\gamma,e)_{Inc}e^{-\sigma_{Inc}\Phi} \qquad (3.3)$$

where

σ_{Inc} is the neutron capture cross-section of Inconel 600 (average by weight of all elements), and
S(n, γ,e) is the initial sensitivity in the detector caused by (n, γ,e) in the emitter.

3.2 Vanadium Detector Burnup

There are four major sources of current in the vanadium in-core flux detectors. They are

1. (n,β) in the vanadium emitter,
2. (n, γ,e) in the vanadium emitter,
3. (n, γ,e) in the Inconel sheath (this is a two-stage process in which neutron capture produces gamma rays in the Inconel sheath, and these gamma rays knock electrons out of the vanadium emitter by (γ,e)), and
4. (γ,e) in the vanadium emitter from external gamma rays (G in Equation 3.1).

For vanadium detectors,

$$A(\phi) = S_V(0)e^{-\sigma_v\phi} + S(n,\gamma,e)_{Inc}\, e^{-\sigma_{Inc}\phi} \tag{3.4}$$

where terms are as described in Equation 3.3 except

σ_V is the neutron capture cross-section of vanadium, and
$S_V(0)$ is the initial sensitivity in the detector caused by (n,β) and (n, γ,e).

For vanadium detectors, $A(\phi)$ is the dominant term in Equation 3.1.

3.3 Platinum Detector Burnup

There are three major sources of current in the platinum in-core flux detectors. They are

1. (n,γ,e) in the platinum emitter,
2. (γ,e) in the platinum emitter (G in Equation 3.1), and
3. (n,γ) in the Inconel sheath followed by (γ,e) from the capture gamma rays in the platinum emitter.

For platinum detectors,

$$A(\phi) = S(n,\gamma,e)_{Pt}e^{-\sigma_{Pt}\Phi} + S(n,\gamma,e)_{Inc}e^{-\sigma_{Inc}\Phi} \tag{3.5}$$

where the variables are as described in Equation 3.3.

The burnup model assumes an average flux of 2×10^{18} n/m^2/s and the variable is then time, that is,

$$A(t) = S(n,\gamma,e)_{Pt}e^{-\sigma_{Pt}\Phi t} + S(n,\gamma,e)_{Inc}e^{-\sigma_{Inc}\Phi t} \tag{3.6}$$

G and $A(\phi)$ are dominant and almost equal. (See Table 4 for experimentally determined values for these terms.)

3.4 Pt-clad Inconel Detector Burnup

There are three major sources of current in the platinum-clad Inconel in-core flux detectors. They are

1. (n,γ,e) in the platinum cladding of the emitter,
2. (γ,e) in the platinum cladding and Inconel (G in Equation 3.1), and
3. (n,γ,e) in the Inconel emitter.

$$A(\phi) = S(n,\gamma,e)_{Pt}e^{-\sigma_{Pt}\phi} + S(n,\gamma,e)_{Inc}e^{-\sigma_{Inc}\phi} \quad (3.7)$$

where the variables are as-described in Equation 3.3.

All three processes have a significant impact on the sensitivity, making this a complicated burnup to examine. The general trend of sensitivity is expected to be as it is for the Inconel detector but with a lower peak sensitivity because of the increased contribution of gamma and platinum to the total detector signal.

4. EXPERIMENTAL RESULTS

4.1 Sensitivity of Vanadium, Inconel, and Platinum-clad Inconel SIR Detectors in NRU

The 13 SIR detectors in NRU were part of the SIR development program at Chalk River in the late 1970's and early 1980's. They were part of numerous experiments in their first years that have been well documented. This makes them ideal for investigating changes in sensitivity caused by long-term exposure to radiation.

The construction characteristics of these detectors are summarized in Table 3. Four detectors have vanadium emitters, two detectors have Inconel emitters, six detectors have platinum-clad Inconel emitters, and one detector has a platinum-clad nickel emitter. The platinum-clad Inconel detectors are in two series (ZC and ED) with different emitter diameters and platinum cladding thickness. Unfortunately, the effect of these construction differences could not be assessed because the original sensitivities were not recorded for one series of platinum-clad Inconel detectors. In general, the emitters of these SIR detectors are about one third the length of those used in CANDU stations. Because sensitivity is independent of length, the changes in sensitivity of these detectors should be representative of those in CANDU stations.

The sensitivity is calculated using the following equation:

$$S = \frac{I}{\left(\frac{\sum_{x=a}^{x=b}\Phi(x)}{b-a}\right)L} \quad (4.1)$$

where

S is the absolute sensitivity of the detector (A/m/n/m^2/s),
I is the current produced by the detector (A),
$\Phi(x)$ is the flux at position x (n/m^2/s),
a and b are the end positions of the detector (in terms of samples), and
L is the length of the detector (m).

The neutron flux is measured using a Travelling Flux Detector (TFD) [6]. The TFD consists of a miniature fission chamber (1/8" o.d.) that can be moved through the core using a cable and winch. SIR assemblies are designed with a tube in the centre of the assembly into which the TFD can be inserted. The TFD is pulled at a rate of 3.5 cm/s through the core and sampled to get readings of neutron flux every 5 mm. This neutron flux is used in Equation 4.1 to calculate the sensitivity of the detectors. The (absolute) accuracy of the sensitivity depends mainly on the accuracy (of the order of a few percent) with which the TFD is calibrated to absolute neutron flux.

Detector current was measured using current-to-voltage amplifiers for the 1995 January measurement and a picoammeter for the 1995 November measurement.

In between the January and November measurements, the assembly with the flux detectors was moved from one lattice location in NRU to another location. The effects of the move are described below.

To characterize the change in sensitivity of the detectors, it was necessary to quantify the neutron fluence they have been exposed to since 1984 January, the last time sensitivity was measured. This was done by multipying the average January 1995 flux over each detector by the total in-core time since 1984 January and the capacity factor of the reactor since 1984 January, calculated assuming a maximum power of 125 MW as measured on 1995 January.

There is the potential for error in this estimate because the estimate assumes the measured flux shape has been the same since 1984 January and that the flux shape scales linearly with thermal power.

4.1.1 Vanadium Detectors

Sensitivity as a function of fluence for the four vanadium detectors is shown in Figure 4. This figure shows that the predicted change in sensitivity closely matches the measured data. Considering the fact that the measurements involve some approximations, the results serve to give confidence that the measurement and prediction is good (to about 5%). We are confident of the prediction for vanadium detectors since they are dominated (90%) by the (n,β) of vanadium.

4.1.2 Inconel Detectors

Sensitivity as a function of neutron fluence for the two Inconel detectors is shown in Figure 5. This figure shows that the sensitivity of the Inconel detectors has not decreased as predicted. Unfortunately, since there are no measurements of sensitivity between the 1984 January and 1995 January measurements, it is not possible to say how the sensitivity changed between the two measurements and whether the sensitivity is at present increasing, decreasing, or remaining constant.

4.1.3 Platinum-Clad Inconel Detectors

Sensitivity as a function of neutron fluence for the four ZC-series platinum-clad Inconel detectors is shown in Figure 6. The data are confused because the detectors were moved to a new location in the core between the 1995 January and 1995 November measurements. It is speculated that the gamma-neutron flux ratio in the new location is considerably less than in the previous location. Because platinum-clad Inconel detectors have a large gamma flux sensitivity, their measured sensitivity drops. The vanadium and Inconel detector sensitivity measurements did not show this change because these detectors have only a small gamma sensitivity.

Therefore, only the 1995 January measurements of platinum-clad Inconel detector sensitivities should be compared with the previous measurements. The 1995 January measurements show that the sensitivity of the platinum-clad Inconel detectors is also greater than predicted. These results are consistent with the Inconel detectors, as is consistent with the fact that both detectors are getting a portion of their signal from Inconel.

Although the long-term change in sensitivity of the ED series of detectors (refer to Table 3) could not be determined, they do show an increased sensitivity compared with the ZC series. The average sensitivity of the ED series detectors was 6.01×10^{-25} A/m/n/m^2/s compared with 5.74×10^{-25} A/m/n/m^2/s for the ZC series detectors. This difference is significant in comparison to the random measurement error, but it is impossible to tell if this difference is due to the construction differences or the difference in total irradiation. As well, the sensitivity of the ED series detectors did not decrease as much after the movement. The average sensitivity of the ED series detectors after the move was 5.34 (an 11% decrease), whereas the average sensitivity of the ZC series detectors was 4.74 (17 % decrease). The difference could be explained if the ED series detectors had a somewhat higher sensitivity to neutron flux.

4.2 Sensitivity of Platinum Coiled Detectors in CANDU

Because the absolute sensitivity of ICFDs in CANDU is not measured, with the exception of the vanadium SIR detectors in CANDU 6 reactors, the sensitivity cannot be tracked as it was in the case of the NRU detectors. However, in the course of doing insulation resistance measurements, the CANDU stations record raw current measurements. These raw current measurements can be used to plot the change in sensitivity of detectors.

For this study, information was available from Bruce A Units 3 and 4 SDS1 and Pickering B Unit 6 SDS1. The Bruce data include both in-service and spare detectors, whereas the Pickering data include only spares. As well, Bruce A data were available from the start of operation of the ICFDs (1984), whereas the Pickering data were from about 5 years after start of operation (1982).

Relative sensitivities were calculated by normalizing currents to the initial current measurements. Then, the relative sensitivities for all detectors in a channel were averaged and fitted to an exponential function. The exponential function was used because the burnup was predicted to be mainly an exponential function of the neutron absorption

cross-section of platinum and total flux seen by the detector (Equation 3.5). An example of the fit compared with the predicted burnup for one channel from Bruce is shown in Figure 7. The other channels were similar.

5. POSSIBLE CAUSES FOR DISCREPANCY BETWEEN MEASURED AND PREDICTED CHANGES IN SENSITIVITY

Section 4 presented experimental results that show consistently that platinum, platinum-clad Inconel, and Inconel detector sensitivity is not decreasing as quickly as predicted by a significant margin. In contrast to this, the agreement between measured and predicted sensitivity of vanadium detectors is good. The fact that the agreement for vanadium is good suggests that the data from NRU are good and that new models need to be developed to predict the complex burnup of platinum, Inconel, and platinum-clad Inconel detectors. Possible changes to the simplest of these, the platinum detector model, are discussed below. Platinum is the simplest because its change in sensitivity is dominated by the burnup of platinum, whereas Inconel and platinum-clad Inconel have multiple burnup mechanisms. For the platinum detectors the discrepancy may be due to both experimental measurement and assumptions in the prediction. Possible sources of this discrepancy are discussed and evaluated below.

Flux Level

The prediction assumes an average flux of 2×10^{18} n/m^2/s. Because the peak flux in a CANDU core is around 3×10^{18} n/m^2/s, this would be equivalent to assuming that the CANDU reactors in the study have a capacity factor of 67%. For the periods in question, the reactors in the study had capacity factors close enough to this assumption to have minimal effect on the overall curve. For this factor to explain the observations, the assumed capacity factor would have to be in error by a factor of 10.

Gamma-Neutron Flux Ratio

The gamma-neutron flux ratio in CANDU reactors differs from that present in NRU when the partial sensitivities used in predicting the burnup curve (see Table 4) were experimentally determined [2]. The burnup from the station measurements was fitted to an exponential function, with the partial sensitivities as free variables. The fit indicated that a partial sensitivity for $S(\gamma,e) / S(0)$ of 0.80 is required to explain the station measurements. This degree of change is not credible.

Self-shielding

Self-shielding reduces the effective neutron capture cross-section of platinum. The effect of self-shielding was shown in rhodium detectors. The ratio of effective cross-section to theoretical cross-section for rhodium was used to determine the effective cross-section of platinum and another burnup calculation was done. The burnup curve was only slightly raised.

Inclusion of all Isotopes of Platinum

The prediction did not take into account all isotopes of platinum that might contribute to the signal and burnup at a different rate. The burnup of all platinum isotopes and daughters was modelled and the effectiveness of various beta emissions was estimated. The results again raised the burnup curve but not enough to account for the measurements. The results of this explanation alone are shown on Figure 7 as the new platinum model.

Table 4 shows the important parameters used in the model and revised values as a result of implementing the above discussed changes. A combination of the changes discussed above were modelled, and the result is shown in Figure 7 as combination platinum model. The model matches the observed sensitivity better than any other model but is still far from adequate.

6. CONCLUSIONS

The change in sensitivity as a function of fluence for vanadium, platinum-clad Inconel, and Inconel SIR detectors was measured using detectors that have been in NRU since at least October 1983. These detectors are of similar construction to the SIR detectors used in CANDU stations except that they are about a third shorter. Because sensitivity is independent of length, this difference is not expected to be significant. This is the first time that measurements of long-term changes in sensitivity of detectors with irradiation have been compared with predictions.

The vanadium detector sensitivity curve matches the prediction reasonably well; however, the platinum-clad Inconel and Inconel detector sensitivities are significantly higher than predicted.

Between the 1995 January and 1995 November measurements, the flux detector assembly in NRU was moved from a mid-lattice position to a position nearer the periphery of the core. The apparent decrease in sensitivity of the platinum-clad Inconel detectors after the move is postulated to be an artifact caused by a decrease in the gamma flux at the new location.

Sensitivity curves have also been shown for platinum coiled detectors in Pickering B and Bruce A. These curves were created from an analysis of current measurements from insulation resistance data. The curves show that the detectors are burning-up at a much slower rate than predicted. Several explanations were put forward and assessed but none adequately explains the smaller-than-predicted reduction in sensitivity.

The reason for the discrepancy between the measured and predicted sensitivity for platinum-clad Inconel and Inconel SIR detectors is also not known. However, it may be assumed that at least some of the mechanisms that cause the discrepancy for platinum are also at work for Inconel and platinum-clad Inconel. Further studies to investigate the discrepancy are needed.

7. ACKNOWLEDGMENTS

The author would like to thank John Hilborn for contributing the appendix and for reviewing the paper. Thanks are also due to Heather Parsons at Bruce A and Risto Vilkko at Pickering B for providing the station data and Paul Kumli for the platinum isotope burnup model.

The wo k reported in this paper was funded by the CANDU Owners Group (COG) R&D Program:

Working Party No. 16 WPIR No. 1633

8. REFERENCES

1. C.J. ALLAN and G.F. LYNCH, "Radiation Induced Currents in Mineral Insulated Cables", IEEE Transactions on Nuclear Science, Vol. NS-27, No. 1, Pg. 660 February 1980.

2. C.J. ALLAN, "Experimental Measurements of Neutron and Gamma-Ray Sensitivities of Flux Detectors Having a Mixed Response", IEEE Transactions on Nuclear Science, Vol. NS-29, No. 1, Pg. 660 February 1982, AECL-7479.

3. D.S. HALL, "Monte Carlo Simulation of Self-Powered Flux Detectors", IEEE Transactions on Nuclear Science, Vol NS-29, No. 1, Pg. 646 February 1982.

4. C.J. ALLAN, "Review of the Dynamic Response of Self-Powered Flux Detectors in CANDU Stations", Proceedings of the 2nd Annual Conference of the Canadian Nuclear Society, Ottawa, Pg. 290 June 1981.

5. C.J. ALLAN, "A New Self-Powered Flux Detector", Atomic Energy of Canada Limited Report, November 1979, AECL-6681.

6. C.J. ALLAN, A.M. MCDONALD, J.M. CUTTLER, and J.H. ERVEN, "The Development and Use of a Travelling Flux Detector System for CANDU Reactors", IEEE Trans. Nuc. Sci., Vol NS-28, No. 1, Pg 720 February 1981, AECL-7206.

Appendix A

Burnup Correction for Vanadium Detector

In a constant neutron flux, the sensitivity of a vanadium detector decreases according to

$$S(t) = S(0)e^{-\sigma\Phi t} \cong S(0)(1-\sigma\phi t) \tag{A.1}$$

where

$S(0)$ = neutron sensitivity at time 0,
$S(t)$ = neutron sensitivity at time t,
σ = burnup cross-section, and
ϕ = neutron flux at the detector.

If the neutron flux varies with time, an approximate expression for the sensitivity is

$$S(t) = S(0) - S(0)\int_0^t \sigma\phi(t)dt \tag{A.2}$$

where

$\phi(t)$ = neutron flux at the detector at time t.

Because $S(0)\,\phi(t)$ is approximately equal to the detector current for a period of years

$$S(t) = S(0) - \sigma\int_0^t Idt = S(0) - \sigma Q(t) \tag{A.3}$$

where

$Q(t)$ = accumulated charge at time t.

At $t = \infty$, $S(t) = 0$ and $Q(t) = Q(\infty) = \frac{S(0)}{\sigma}$

Hence

$$S(t) = S(0)\left(1 - \frac{Q(t)}{Q(\infty)}\right) \tag{A.4}$$

The plot of S(t) versus Q(t) should be a straight line intersecting the Q(t) axis at $Q(\infty)$ (Figure A.1). In most cases, recording the vanadium current once or twice a day would be adequate for time integration. In effect, the recorded current signal from each detector provides an individual sensitivity correction for each detector over its entire lifetime in the reactor.

Periodic calibrations with a TFD over a period of years will determine the accuracy of the simple linear correction formula. If necessary, an empirical quadratic term can be added.

TABLE 1. RESPONSE CHARACTERISTICS OF IN-CORE FLUX DETECTORS

Type	Response to (n, β)	Response to (n, γ, e)	Response to (γ, e)
Platinum (coiled)	-3%	58%	42%
Vanadium (SIR)	92%	8%	0%
Pt-clad Inconel (SIR)	-3%	61%	39%
Inconel (SIR)	0%	110%	-10%

TABLE 2. TYPICAL IN-CORE FLUX DETECTORS SENSITIVITY AT START OF LIFE

Detector Type	Typical Sensitivity (A/(n/m^2/s)/m)
Platinum coiled	5×10^{-25}
Vanadium SIR	30×10^{-25}
Platinum-clad Inconel SIR	4.5×10^{-25}
Inconel SIR	2.5×10^{-25}

TABLE 3. CONSTRUCTION CHARACTERISTICS OF SIR DETECTORS IN NRU

Identity	Type	Emitter Length (mm)	Emitter Diameter (mm)	Platinum Thickness (mm)	Date Installed in NRU
ED-9	Pt-clad Inc	304	1.66	0.050	83/10/26
ED-10	Pt-clad Inc	314	1.66	0.050	83/10/26
ED-11	Pt-clad Ni	522	1.75	0.050	83/10/26
ZC0603	Pt-clad Inc	301.5	1.43	0.109	82/01/20
ZC0605	Pt-clad Inc	300	1.44	0.111	82/01/20
ZC0606	Pt-clad Inc	290	1.46	0.110	82/03/04
ZC0608	Pt-clad Inc	300.5	1.44	0.106	82/03/04
YC1203	Vanadium	98	1.44	NA	81/07/02
YC1204	Vanadium	101	1.44	NA	81/07/02
YC1206	Vanadium	99.5	1.44	NA	81/07/02
YC1207	Vanadium	100.5	1.44	NA	81/07/02
YC1214	Inconel	300	1.72	NA	81/10/19
WL24112 (D)	Inconel	870	1.68	NA	82/10/21

TABLE 4. PARAMETERS USED IN THE PLATINUM BURNUP MODEL

Parameters	Original Model Values	New Model Values
$S(n,\gamma,e)_{Pt}/S(0)$	0.50	0.44
$S(\gamma,e)/S(0)$	0.42	0.50
$S(n,\gamma,e)_{Inc}/S(0)$	0.08	0.06
σ_{Pt}	27 barns	23 barns
σ_{Inc}	4.6 barns	4.6 barns

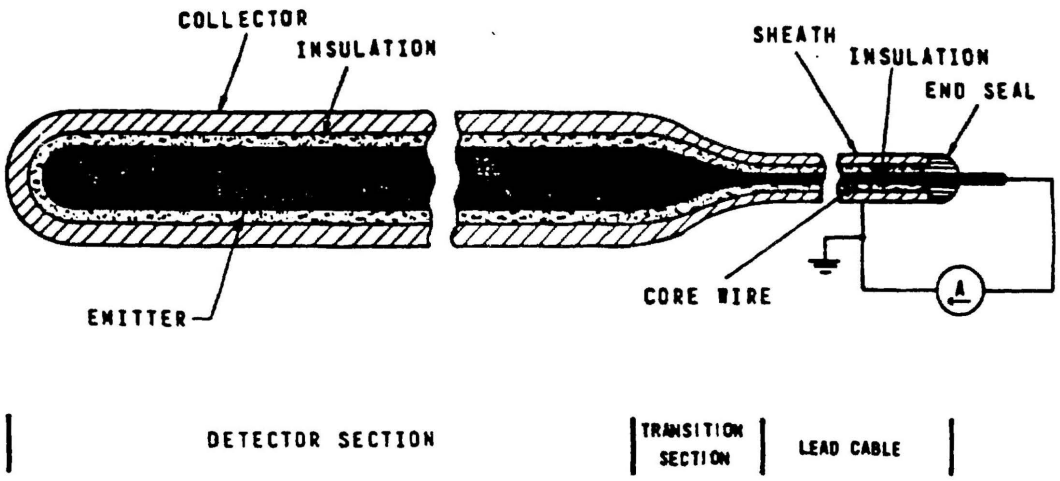

FIGURE 1. IN-CORE FLUX DETECTOR CONSTRUCTION

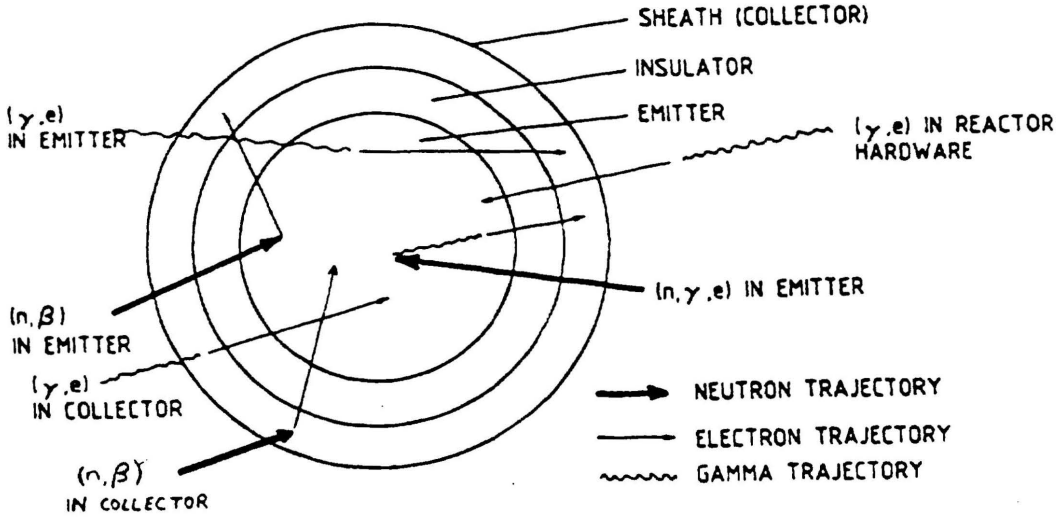

FIGURE 2. ATOMIC INTERACTIONS IN AN IN-CORE FLUX DETECTOR

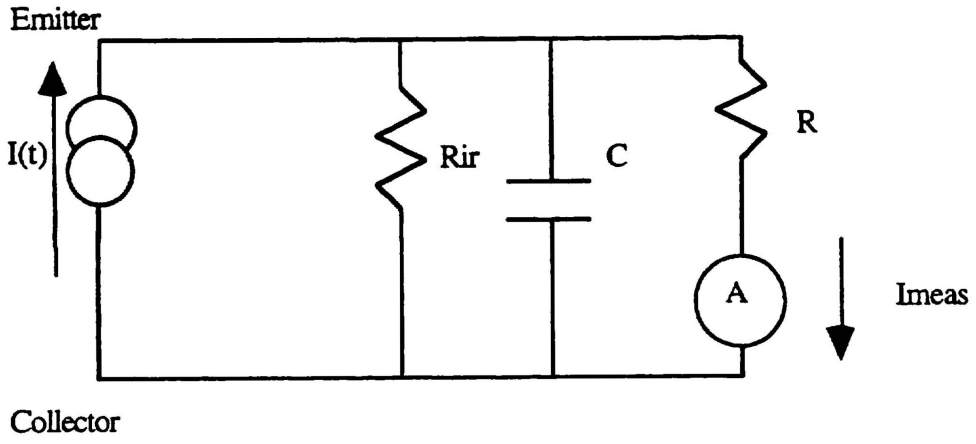

FIGURE 3. ELECTRICAL MODEL OF AN IN-CORE FLUX DETECTOR

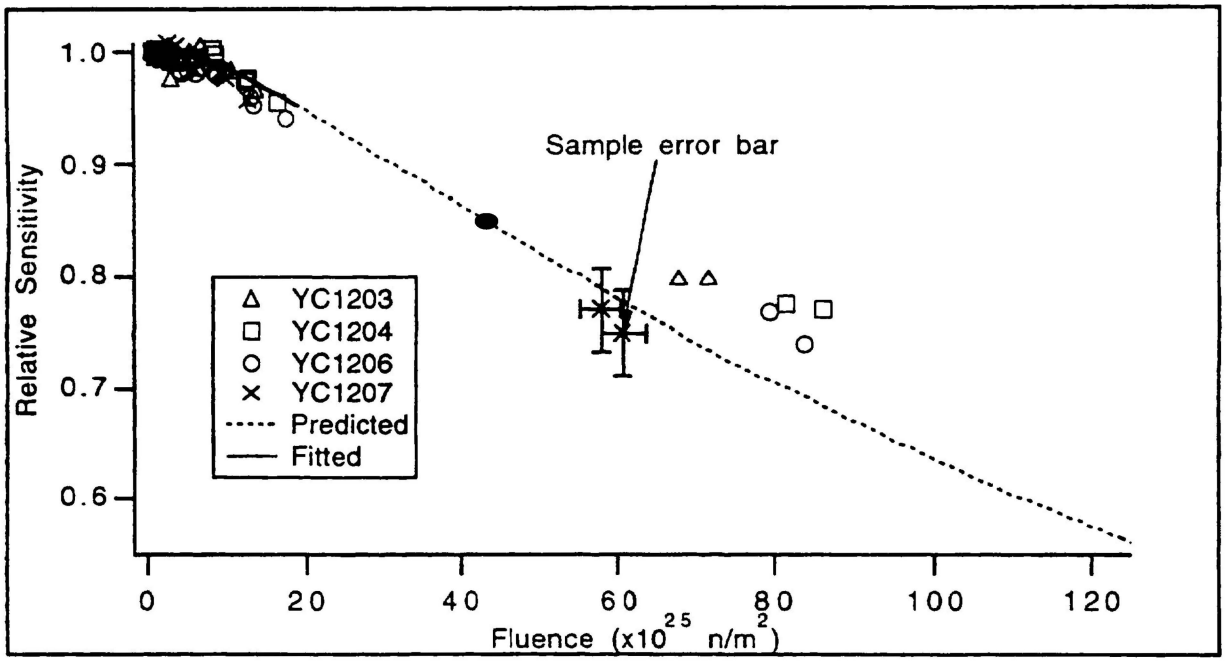

FIGURE 4. VANADIUM SIR MEASURED AND PREDICTED CHANGE IN SENSITIVITY WITH FLUENCE

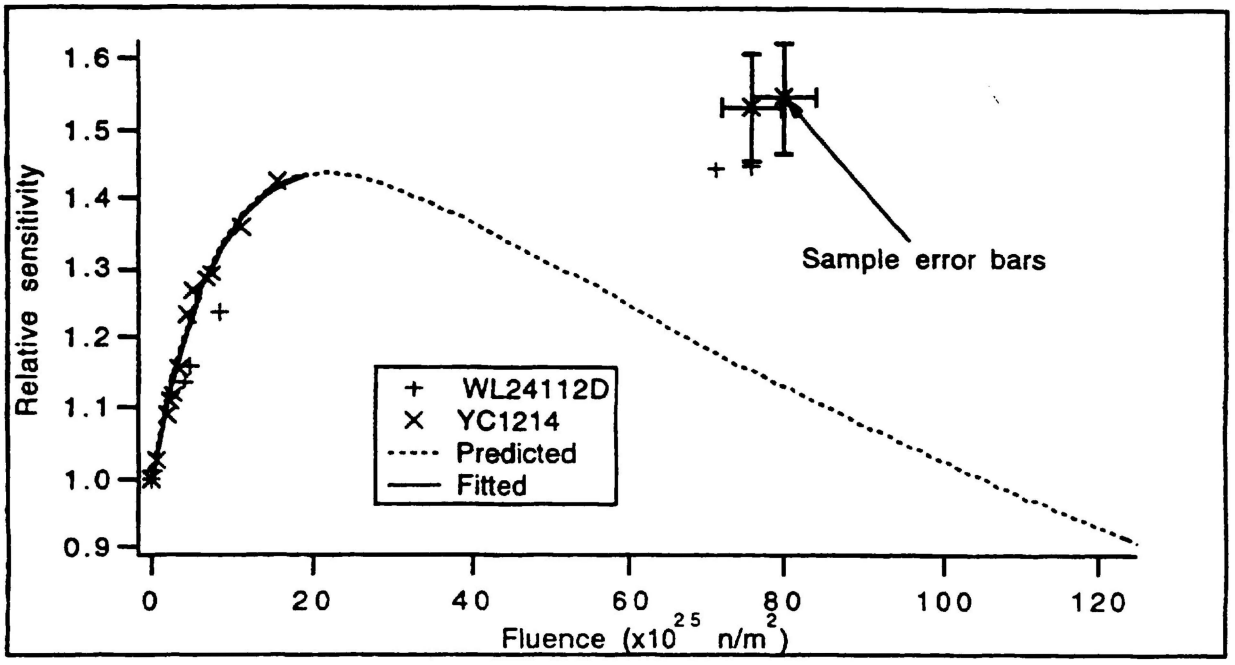

FIGURE 5. INCONEL SIR MEASURED AND PREDICTED CHANGE IN SENSITIVITY WITH FLUENCE

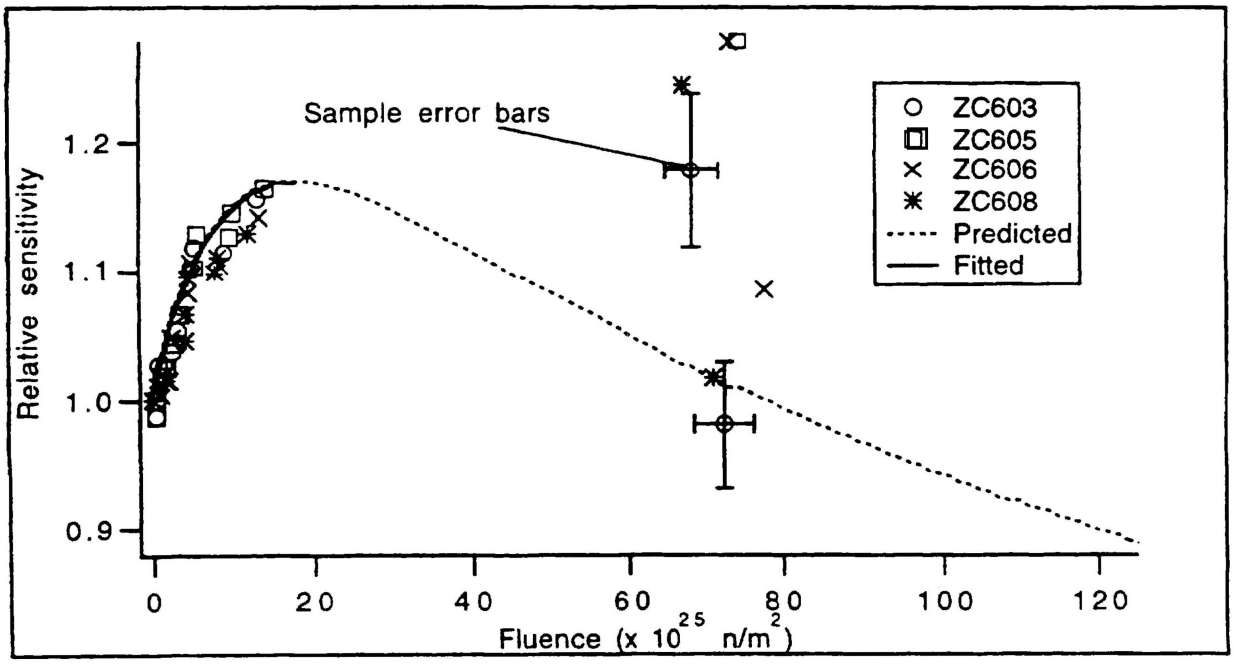

FIGURE 6. PLATINUM-CLAD INCONEL SIR MEASURED AND PREDICTED CHANGE IN SENSITIVITY WITH FLUENCE

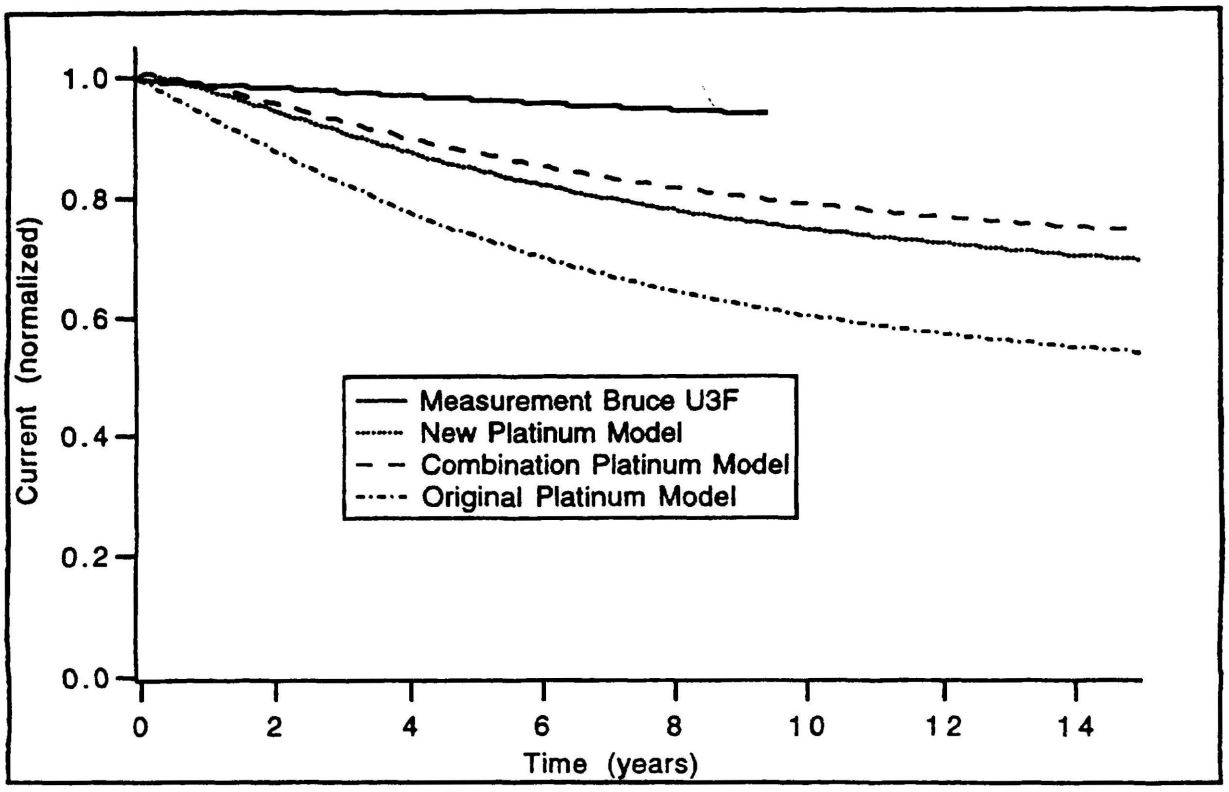

FIGURE 7 PLATINUM MEASURED, PREDICTED, AND MODIFIED CHANGE IN SENSITIVITY WITH FLUENCE

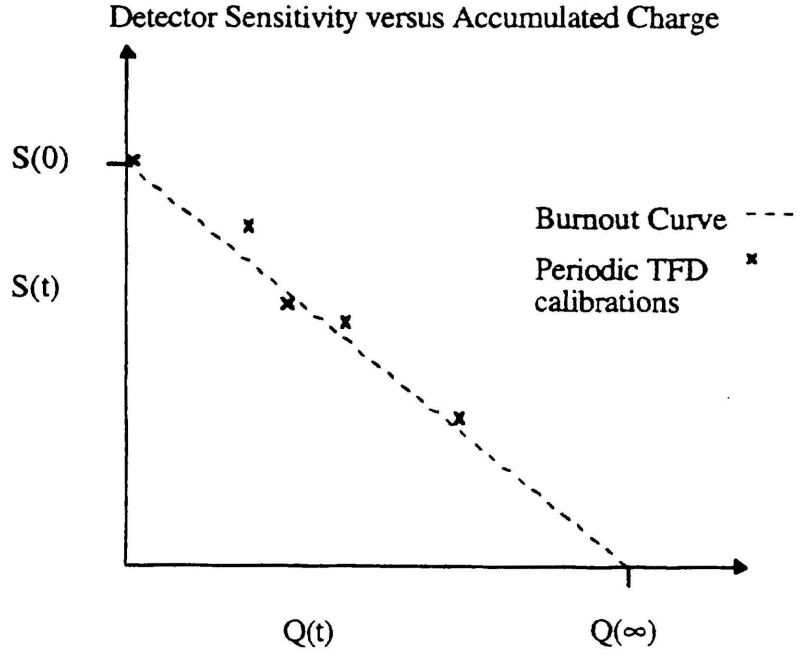

FIGURE A.1 TYPICAL VANADIUM BURNOUT CURVE