IN-SITU CALIBRATION OF FLUX MAPPING DETECTORS IN AN OPERATING CANDU REACTOR

T.C. LEUNG, D.S. HALL, N.H. DREWELL
Atomic Energy of Canada Limited

and

A.M. Lopez
Ontario Hydro

ABSTRACT

A transportable Travelling Flux Detector (TFD) system designed for the in-situ calibration of fixed self-powered detectors has been developed and tested at Chalk River. This paper describes the first successful use of the computerized TFD system in an operating CANDU power reactor and the results obtained from the in-situ calibration of the 54 vanadium flux mapping detectors in the Bruce B, Unit 6 reactor. The measured detector sensitivities agree with the power law correlation previously determined in the ZED-2 zero energy experimental reactor at the Chalk River Nuclear Laboratories.

INTRODUCTION

Self-powered flux detectors are used extensively in CANDU power reactors. Detectors with vanadium emitters are used for flux mapping while those with platinum, Inconel or Pt-Clad Inconel emitters are used for bulk and spatial flux control and for overpower protection (1,2). The detectors used in the Pickering, Bruce A and 600 MWe reactors are coiled on a Zircaloy carrier tube. In this design, some spare detectors are provided on each detector assembly carrier tube, as individual detectors cannot be replaced. In Bruce B and Darlington, the detectors are inserted straight into individual Zircaloy guide tubes so that individual detectors can be replaced with the reactor at power. Since the detectors used are Straight and Individually Replaceable, the acronym SIR has been adopted to describe both the detectors and assembly (3).

In parallel with the development of the SIR detectors, a transportable Travelling Flux Detector (TFD) system, designed for the in-situ calibration of the fixed self-powered detectors, has also been developed at Chalk River. The initial development program was completed in 1979, and a prototype TFD system was installed in the NRU research reactor at CRNL for the in-situ calibration of test detectors and to measure their dynamic response (4,5). However, at this stage of development, although the SIR assemblies in Bruce B have been designed to accomodate a TFD system, the prototype TFD system itself was not fully developed to meet all the requirements for use in power reactors. In order to facilitate its use in operating CANDU power reactors, the TFD system was converted to computer control. Computer hardware was acquired and powerful software developed to control the TFD drive mechanism. The data acquisition system was upgraded by replacing the original data logger by a much more sophisticated computer system.

This paper describes the first successful use of the computerized TFD system in an operating CANDU power reactor and the results obtained from the in-situ calibration of the 54 vanadium flux-mapping detectors in the Bruce B, Unit 6 reactor.

EXPERIMENTAL

SIR Flux Detector Assembly

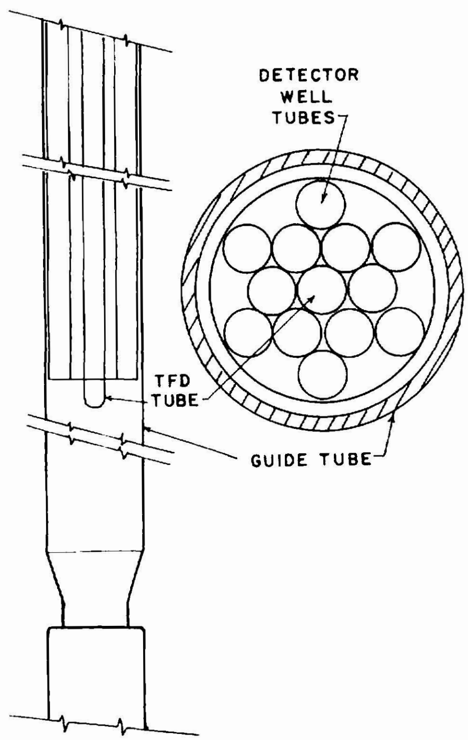

Figure 1 SCHEMATIC REPRESENTATION OF A FLUX DETECTOR ASSEMBLY

Figure 1 shows a typical SIR flux detector assembly in which a dry helium environment for the detectors is maintained inside the 20.4 mm OD Zircaloy guide tube. Flux detectors (3.0 mm OD) can be inserted individually into the twelve open-ended Zircaloy well tubes, (3.4 mm ID x 3.8 mm OD), by pushing the lead cables of the detectors until the required location in the core is reached. Each lead cable terminates in its own connector which is plugged into the appropriate receptacle in the connector housing at the top of the assembly. The central well tube is reserved to accommodate a travelling flux detector, a 3.0 mm OD fission chamber, for the in-situ calibration of the fixed detectors. The central tube is sealed at the bottom to isolate it from the helium atmosphere surrounding the fixed detectors.

In the Bruce B, Unit 6 reactor, there are 27 vertical detector assemblies. The layout of the detector assemblies is shown in Figure 2.

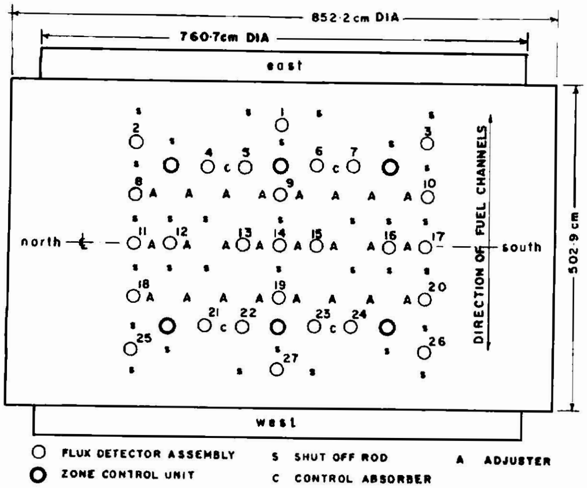

FIGURE 2 LAYOUT OF THE FLUX DETECTOR ASSEMBLIES

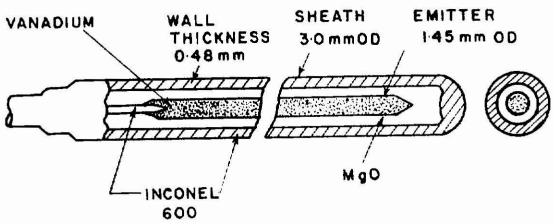

FIGURE 3 THE VANADIUM FLUX MAPPING DETECTOR

The Vanadium Flux-Mapping Detectors

The in-core flux detectors used in CANDU reactors are the self-powered type. The self-powered detector is essentially a co-axial cable consisting of an inner emitter electrode, and an outer collector electrode, separated from each other by an annular insulator. It is "self-powered" because it does not require an applied bias voltage to separate and collect ionization charge to derive a signal.

Figure 3 shows a schematic representation of a vanadium in-core flux detector. The detector length is 286 mm, i.e. one lattice pitch. The locations of the Bruce B flux mapping detectors are shown in Figures 4A to 4C.

Vanadium detectors are not suitable for use in safety or control systems because of their slow dynamic response characteristics (6). However, they are well suited for flux mapping in CANDU reactors. The vanadium absorption cross section is inversely proportional to the neutron velocity (varies as 1/v), and hence the output current from a vanadium detector provides a good measure of the thermal neutron flux.

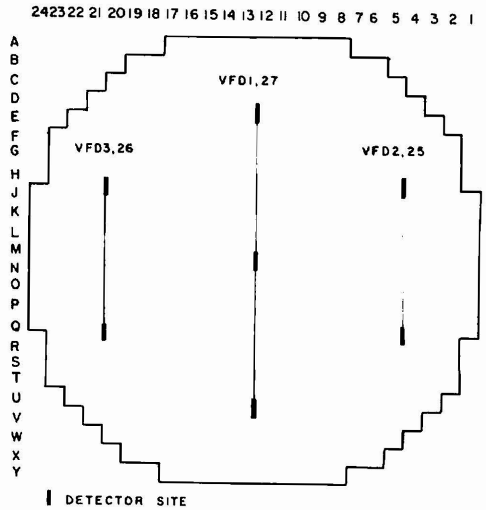

FIGURE 4A BRUCE B FLUX-MAPPING DETECTOR LOCATIONS, OUTER GROUP

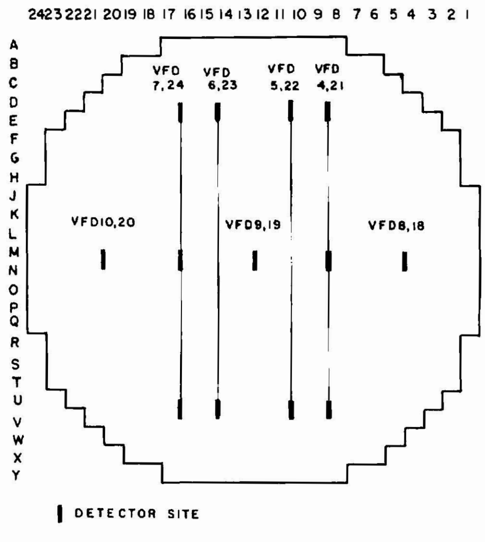

FIGURE 4B BRUCE B FLUX-MAPPING DETECTOR LOCATIONS, MID GROUP

Flux mapping (7,8) is a spatial interpolation and smoothing technique which processes the signals from 54 vanadium in-core flux detectors to obtain three-dimensional maps of the flux and power distribution in the reactor core. In Bruce B, the flux mapping system supplies an effective peak-flux signal to the automatic reactor regulating system for setback purposes. The high-local-flux setback used in the Bruce design provides automatic reactor-power reduction whenever the estimated peak bundle power increases above pre-set limits. This setback replaces pre-set bulk-reactor-power limits in the earlier Pickering design. While the Bruce setback

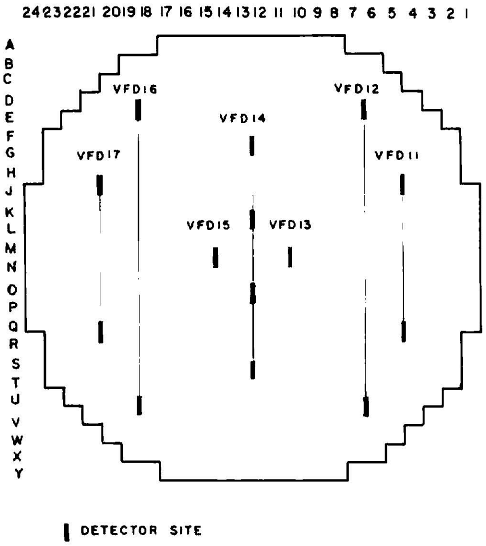

FIGURE 4C BRUCE B FLUX-MAPPING DETECTOR LOCATIONS, CENTRAL GROUP

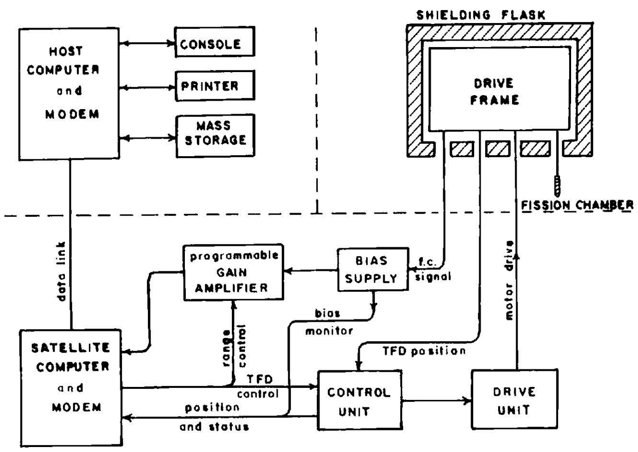

FIGURE 5 BLOCK DIAGRAM OF THE TFD SYSTEM

action is based on estimated bundle power, it carries with it implicit limiting of channel powers and provides a degree of self-protection within the reactor regulating system from slow spatial loss of regulation.

In addition to its setback role, the flux mapping system in Bruce B provides, on operator request, displays of the mapped three-dimensional flux distribution, mapped channel powers and mapped integrated flux for the reactor spatial-control zones. These maps are useful aids in performing day-to-day fuel management tasks and in diagnosing and correcting any problems encountered with reactor spatial control.

Description of TFD System

The TFD system is illustrated schematically in Figure 5. It consists of a number of interacting sub-systems that include the following:

(i) a miniature fission chamber;
(ii) a drive mechanism for moving the fission chamber;
(iii) a satellite computer system for controlling the drive mechanism and for receiving raw data; and
(iv) a data acquisition system for utilizing and storing the data.

The fission chamber is the Westinghouse WX-33073 type, 36 mm in length and 3.0 mm OD. The chamber is constructed of stainless steel with high-purity alumina insulation and will operate at ambient temperatures up to 400°C. The detector is connected to a lead cable with an Inconel 600 jacket and magnesium oxide insulation.

The drive mechanism consists of: a drum on which the mineral-insulated (MI) lead cable of the fission chamber is wound; a shaft encoder that digitizes the angular displacement of the drum and therefore the position of the fission chamber; and a stepping motor that moves the drum. Because the fission chamber and its lead cable become active during use, the drive mechanism is housed in a lead flask, weighing approximately 3 Mg.

The stepping motor is controlled by an LSI 11/23 satellite-computer system that sends signals to the stepping motor to select the desired speed and direction of motion of the fission chamber. The satellite computer also collects position data from the shaft encoder and the current signal from the fission chamber via a gain-programmable amplifier and an analog-to-digital converter (ADC). The output of the ADC is used to adjust the gain of the amplifier to keep it from over- or under-ranging.

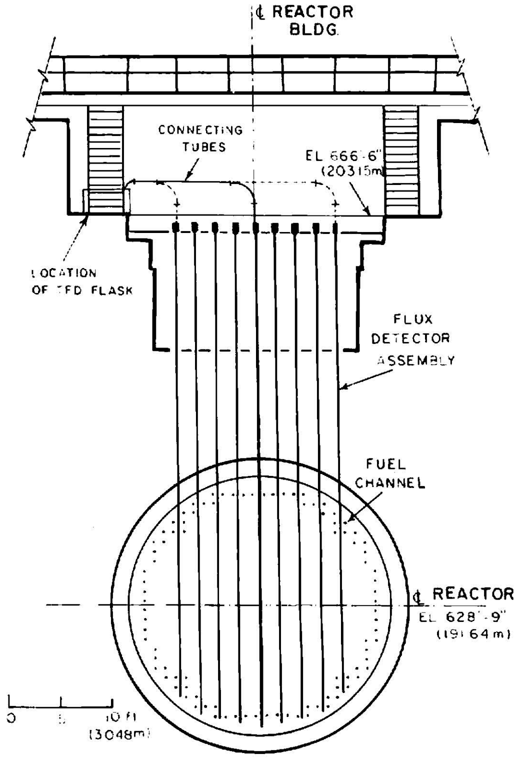

FIGURE 6 ELEVATION VIEW OF REACTOR

A host computer acts as the data acquisition system and as a control console for the system operator. It is located remotely from the drive mechanism. Instructions fed into the master computer are transferred to the satellite computer via a communication link. The fission chamber data, i.e. position and current, are also transferred over the communication link to the host computer for data reduction and/or storage. Operator-selectable parameters include the direction of motion, speed of travel, and data collection rate.

Manual operation of the system is also possible in the event that the computer controls are either unavailable or unwanted. Further details on the TFD system can be found in References 9 and 10.

Scanning Procedure

The TFD drive unit was set beside the reactor deck and suitable lengths of ¼ inch stainless steel tubing were used to route the TFD fission chamber to the appropriate flux detector assemblies (See Fig. 6) The satellite computer was located on the east side catwalk above the reactivity mechanism deck, while the host computer which has a mass storage device and a system console, was installed in an air-conditioned instrument room away from the high radiation environment. For signal and control communication, two shielded twisted pairs of wire were installed between the reactor deck and the instrument room.

In order to calibrate the vanadium flux mapping detectors, the following procedure was used. The reactor power of the 885 MWe Bruce B, Unit 6 was held constant for a few hours before measurements were taken. Each of the vanadium detector signals was read into the station computer in the control room before and after each TFD scan. The TFD fission chamber was driven into the detector assembly in the reactor core at a speed of 50 mm/s and the output current was monitored at 20 millisec intervals to yield a data point at every millimeter. Data were taken on both in-scan and out-scan of the reactor.

Apart from an initial unexpected problem with electrical noise, the equipment and the computer system performed very well in the harsh environment of the power station. During the first trial scan, the fission chamber read a steady 100 A current. The signal was traced to a very small negative signal at the Analog to Digital Converter (ADC) and the noise signal persisted intermittently with new electrical ground connections. In the end, the entire system was connected to a single ground at the reactor deck, and when the true fission-chamber signal exceeded 10^{-8} A, the computer processed signal was normal. A total of twenty-seven vertical detector assemblies were scanned over their full length. An additional scan on one assembly in the central region of the core was performed to check reproducibility.

Data Analysis

The basic equation to determine the sensitivity (current per unit flux per unit length), S, of a flux mapping detector is:

$$S = F\, I\, S_{ref} \Big/ \int_a^b I_{ref}(x)\, dx \qquad [1]$$

where - S_{ref} is the absolute sensitivity of the TFD fission chamber,

- $I_{ref}(x)$ is the current from the TFD at elevation x,
- I is the current generated by the flux mapping detector at the time of calibration,
- a, b are the elevations at the ends of the flux mapping detector,
- F is a factor introduced to correct for the flux depression produced by the detector itself. It is usually a small effect and F is assumed to be unity.

The integral in Equation (1) was calculated by a Riemann sum technique:

$$\int_a^b I_{ref}(x)\, dx \cong T_1 + \sum_i \tfrac{1}{2} \left(I_{ref}(i+1) + I_{ref}(i)\right)\left(x_{i+1} - x_i\right) + T_2 \qquad [2]$$

where - $a < x_i < x_{i+1} < b$

- I_{ref} (i) is the value of the TFD current at x_i, and
- T_1 and T_2 are correction terms, based on linear interpolation, to allow for the fact that the elevations of the ends of the detector do not necessarily correspond to the elevations at which the TFD readings were taken.

Figure 7 shows a typical current profile $I_{ref}(x)$ near a detector. A FORTRAN program has been written to perform the numerical integration of the TFD current between the detector end points. Typical values for I and $\int_a^b I_{ref}(x)\, dx$ were 1.7×10^{-6} A and 0.63×10^{-4} A.m respectively. S_{ref} for the TFD fission chamber has been calibrated in the thermal column of the NRU reactor at Chalk River to be 1.205×10^{-22} A/(n.m^{-2}s^{-2}). The sensitivities of the 54 vanadium detectors were then determined using Eq. (1).

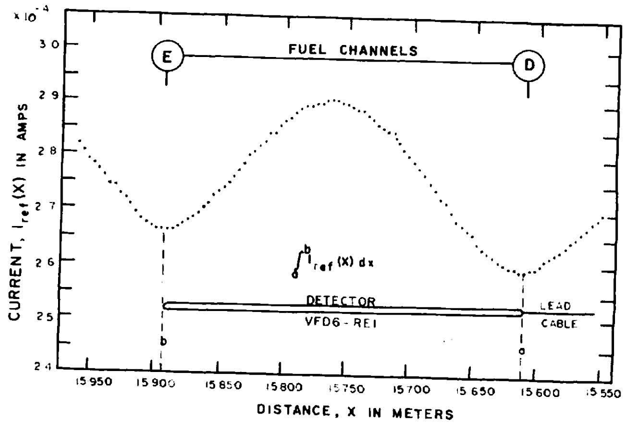

FIGURE 7 A TYPICAL CURRENT PROFILE NEAR A DETECTOR

RESULTS AND DISCUSSION

Table 1 gives a summary of the sensitivities of the 54 vanadium flux-mapping detectors in the Bruce B, Unit 6 reactor. The average sensitivity is $(3.21 \pm 0.08) \times 10^{-24}$ A.m^{-1}/(n.m^{-2}s^{-1}). The spread of the data is due to the statistical variation in length and material composition of the detectors. Also, detectors at different locations in the core are subjected to burn up at different rates,

TABLE 1 SUMMARY OF BRUCE B, UNIT 6 FLUX-MAPPING DETECTOR SENSITIVITIES

#	Assembly Detector No.	Sensitivity $(10^{-24}\ A.m.^{-1}/n.m^{-2}.s^{-1})$	#	Assembly Detector No.	Sensitivity $(10^{-24}\ A.m^{-1}/n.m^{-2}.s^{-1})$
1	VFD1 RE2	3.13	28	VFD14 RE4	3.30*
2	VFD1 RE4	3.18	29	VFD14 RE5	3.21*
3	VFD1 RE9	3.41	30	VFD15 RE2	3.19
4	VFD2 RE1	3.26	31	VFD16 RE1	3.09
5	VFD2 RE7	3.33	32	VFD16 RE4	3.27
6	VFD3 RE3	3.18	33	VFD17 RE1	3.11
7	VFD3 RE7	3.22	34	VFD17 RE4	3.17
8	VFD4 RE1	3.11	35	VFD18 RE2	3.16
9	VFD4 RE2	3.10	36	VFD19 RE2	3.22
10	VFD4 RE3	3.27	37	VFD20 RE2	3.15
11	VFD5 RE1	3.13	38	VFD21 RE1	3.14
12	VFD5 RE3	3.25	39	VFD21 RE2	3.18
13	VFD6 RE1	3.14	40	VFD21 RE3	3.32
14	VFD6 RE3	3.30	41	VFD22 RE1	3.14
15	VFD7 RE1	3.15	42	VFD22 RE3	3.32
16	VFD7 RE2	3.16	43	VFD23 RE1	3.13
17	VFD7 RE3	3.27	44	VFD23 RE3	3.26
18	VFD8 RE2	3.18	45	VFD24 RE1	3.12
19	VFD9 RE2	3.21	46	VFD24 RE2	3.13
20	VFD10 RE2	3.13	47	VFD24 RE3	3.25
21	VFD11 RE1	3.22	48	VFD25 RE4	3.24
22	VFD11 RE4	3.22	49	VFD25 RE7	3.28
23	VFD12 RE1	3.15	50	VFD26 RE4	3.20
24	VFD12 RE4	3.32	51	VFD26 RE7	3.27
25	VFD13 RE2	3.25	52	VFD27 RE2	3.08
26	VFD14 RE2	3.16*	53	VFD27 RE5	3.19
27	VFD14 RE3	3.24	54	CFD27 RE9	3.36

* Average value of May 13 and 14, 1986.

TABLE 2
REPRODUCIBILITY OF DETECTOR SENSITIVITIES ON 2 CONSECUTIVE DAYS

Detectors	Sensitivity $10^{-24}.Am^{-1}/(n.m^{-2}s^{-1})$ May 13	May 14	% Change
VFD14 RE2	3.15	3.18	0.95%
VFD14 RE3	3.23	3.26	0.87%
VFD14 RE4	3.29	3.31	0.70%
VFD14 RE5	3.19	3.22	0.78%

determined by the local flux to which they are exposed. Since the Bruce B, Unit 6 reactor was at power for only about a year, one does not expect large variation of sensitivities due to the effect of burnup. However, after 5 to 6 years, the spread of the detector sensitivities will be larger due to different detector burnups.

It is interesting to note that since each detector is one lattice pitch long, the integral $\int_a^b I_{ref}(x)\,dx$, and consequently the detector response, is relatively insensitive to the exact location of the detector. It is estimated that even if there is an error of a few mm in the locations of detector ends, a or b, the integral changes by less than 0.2%.

The reproducibility of detector sensitivities was checked by performing two TFD scans on the central flux-detector assembly on two consecutive days. The results are given in Table 2. The change in flux-mapping detector sensitivity was found to be less than 1%.

The sensitivities of a variety of vanadium self-powered detectors have been determined by C.J. Allan (11) in a simulated CANDU core installed in the ZED-2 reactor at Chalk River. It was found that the detector sensitivities, S, depend primarily on emitter diameter and that the observed variations can be fitted by means of a power law,

$$S = 2.05 \times 10^{-24} D^{1.23} \qquad [3]$$

where D is the emitter diameter in mm.

The sensitivities of the vanadium flux-mapping detectors in the Bruce B, Unit 6 reactor are in good agreement with this power law correlation, as shown in Figure 8.

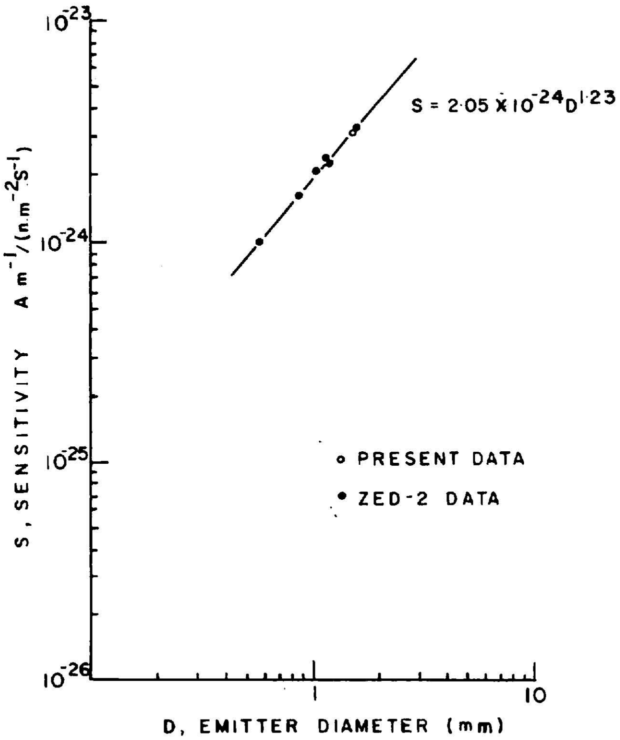

FIGURE 8 VARIATION OF SENSITIVITY WITH EMITTER DIAMETER FOR VANADIUM DETECTORS

CONCLUSIONS

The three conclusions drawn from this work are as follows:

(1) The transportable TFD system is a convenient tool for the in-situ calibration of self-powered flux detectors in operating CANDU power reactors that are equipped with SIR detector assemblies.

(2) Detector sensitivities obtained through in-situ calibration will improve the accuracy of the on-line flux mapping program in calculating the peak channel power output and the high-local-flux set-back signal to the automatic reactor regulating system.

(3) The measured sensitivities of the vanadium flux mapping detectors in Bruce B, Unit 6 agree with the power law correlation previously determined in the ZED-2 reactor.

ACKNOWLEDGEMENTS

This work was financially supported by Ontario Hydro. The measurement was made possible by the co-operation and effort of groups at CANDU Operations, Chalk River Nuclear Laboratories and Ontario Hydro.

The authors would like to acknowledge the co-operation of Bruce B Generating Station staff, in particular C. Olive, K. Rody and D. Clark. A. McDonald of CANDU Operations and I.L. McIntyre and D.A. Kettner of CRNL provided tireless help in organizing and arranging the experiments. C.J. Allan of CRNL, who had initiated this project, provided continuous encouragement and guidance throughout the planning of the experiments. D.A. Kettner and S. Shinmoto of CRNL also took part in the actual experimental work at site.

REFERENCES

1) Lepp, R.M. and Watkins, L.M., "Control and Instrumentation Systems for the 600 MWe CANDU PHW Nuclear Power Plants", AECL Report, AECL-7519 (1982).

2) Allan, C.J., Drewell, N.H., and Hall, D.S., "Recent Advances in Self-Powered Flux Detector Development for CANDU Reactors", Proceedings of an International Symposium on Nuclear Power Plant Control and Instrumentation, Munich, Oct. 11-15, 1982. Paper No. IAEA-SM-265/8., IAEA (1983).

3) Cuttler, J.M. and Erven, J.H., "An Improved In-Core Flux Detector Assembly for CANDU Reactors", Am. Nuc. Soc. Transaction Vol. 34. pp. 585-586 (1980).

4) Hall, D.S., and Shinmoto, S., " A Computer-Controlled Travelling Flux Detector System for CANDU Reactors", IEEE Trans. Nucl. Sci, NS-31, pp. 749 (1984).

5) Allan, C.J., McDonald, A.M., Cuttler, J.M. and Erven, J.H "The Development and use of a Travelling Flux Detector System for CANDU Reactors", IEEE Trans. Nucl Sci. NS 28, pp. 720, (1981).

6) Allan, C.J., "A Review of the Dynamic Response of Self-Powered Flux Detectors in CANDU Reactors," Proc. 2nd Annual Conference Canadian Nuclear Society , Ottawa, Ontario, (1981).

7) Kugler, G.,"Flux Mapping in Bruce A", Atomic Energy of Canada Power Projects Report TDAI-89, Sheridan Park, August (1975).

8) Papadatos, K., McDonald, A., and Fieguth W., "Power Measurements in CANDU Reactors," Proc. 1st Annual Conference Canadian Nuclear Society, Toronto, Ontario (1980).

9) Shinmoto, S., and Hall, D.S., "A Computer-Controlled Travelling Flux Detector System: Design, Operating and Service Manual", CRNL Report CRNL-2489 (1983).

10) Hall, D.S., "A Computer-Controlled Travelling Flux Detector System Software Description and User's Guide, CRNL Report, CRNL-2490 (1983).

11) Allan, C.J., "Response Characteristics of Self-Powered Flux Detectors in CANDU Reactors," AECL Report, AECL-6171 (1978).