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ATOMIC ENERGY OF CANADA LIMITED

L'ÉNERGIE ATOMIQUE DU CANADA LIMITÉE

A HIGH-SPEED DATA ACQUISITION SYSTEM TO MEASURE LOW-LEVEL CURRENT FROM SELF-POWERED FLUX DETECTORS IN CANDU NUCLEAR REACTORS

Système rapide d'acquisition de données pour mesurer les courants faibles provenant des détecteurs de flux auto-alimentés dans les réacteurs nucléaires CANDU

C.B. LAWRENCE and D.S. HALL

Paper presented at the 1982 Canadian Conference on Industrial Computers,
McMaster University, Hamilton, Ontario, 1982 May 3-5

Chalk River Nuclear Laboratories Laboratoires nucléaires de Chalk River

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Résumé

On utilise des détecteurs de flux auto-alimentés dans les réacteurs de puissance CANDU pour déterminer la répartition spatiale du flux neutronique dans le coeur du réacteur à l'usage des systèmes de contrôle et de sécurité du réacteur. Pour établir la réponse dynamique des différents types de détecteurs de flux, les Laboratoires nucléaires de Chalk River ont un programme permanent d'irradiation expérimentale dans le réacteur de recherche NRU pour lequel un système d'acquisition de données a été développé.

Le système décrit dans ce rapport sert à mesurer les courants provenant des détecteurs à un intervalle d'enregistrement régulier et lent ainsi qu'à un taux adaptif rapide, suite à l'arrêt du réacteur. Les courants qui vont de 100 pA à 1 mA, grandeur nature, peuvent être mesurés à partir d'un maximum de 38 détecteurs et stockés à des taux d'échantillonnage atteignant au maximum vingt échantillons par seconde. Les caractéristiques dynamiques des détecteurs peuvent, ensuite, être calculées à partir des enregistrements stockés.

Le système d'acquisition des données comprend un micro-ordinateur DEC LSI-11/23, des disques à double cartouche, des disquettes, une sortie sur papier et un terminal à affichage vidéo. On utilise le système fonctionnel RT-11 et tous les programmes d'application sont écrits en FORTRAN.

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A HIGH-SPEED DATA ACQUISITION SYSTEM TO MEASURE LOW-LEVEL CURRENT FROM SELF-POWERED FLUX DETECTORS IN CANDU NUCLEAR REACTORS

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Self-powered flux detectors are used in CANDU nuclear power reactors to determine the spatial neutron flux distribution in the reactor core for use by both the reactor control and safety systems. To establish the dynamic response of different types of flux detectors, the Chalk River Nuclear Laboratories have an ongoing experimental irradiation program in the NRU research reactor for which a data acquisition system has been developed.

The system, described in this paper, is used to measure the currents from the detectors both at a slow, regular logging interval, and at a rapid, adaptive rate following a reactor shutdown. Currents that range from 100 pA to 1 mA full scale can be measured from up to 38 detectors and stored at sampling rates of up to 20 samples per second. The dynamic characteristics of the detectors can then be computed from the stored records.

The data acquisition system comprises a DEC LSI-11/23 microcomputer, dual cartridge disks, floppy disks, a hard copy and a video display terminal. The RT-11 operating system is used and all application programs are written in FORTRAN.

INTRODUCTION

A self-powered flux detector (SPD) is a co-axial cable assembly in which a current is induced when it is placed in a radiation field. In CANDU nuclear reactors they are distributed in the reactor core to measure the magnitude of the neutron flux. The output current of the detector is proportional to the number of neutrons and γ-rays impinging on the co-axial assembly. The detector signals are correlated to the power level of the reactor fuel and are the primary input to the reactor spatial control system that adjusts neutron absorbers to control power. SPDs are also used in the independent overpower protective system.

To design and assess the control and protective systems requires a detailed knowledge of the dynamics of all components in the system, including the SPDs since they are the primary sensing elements in both systems.

The experimental irradiation program in the NRU reactor at the Chalk River Nuclear Laboratories (CRNL) is aimed at understanding the factors affecting SPD performance, such as their dynamic response, to enable their operation to be modelled. The data acquisition system described here is used to acquire data from SPDs to study such things as:

- the dynamic response of detectors which is of interest in its own right but which also provides insight into mechanisms determining their response,
- the response of the detector lead cables,
- cross-talk between detectors,
- the change in detector performance with irradiation, over long periods of time, as various elements in the detector transmute in the high neutron flux.

Not only must the detector characteristics be measured, but small changes with time must be detected to give insight into how detector performance can be expected to change during the 30 year life of a nuclear station.

THE SELF-POWERED FLUX DETECTOR

A schematic diagram of a self-powered flux detector and its integral lead cable is shown in Figure 1. The detector is a co-axial cable with a metallic outer sheath, usually Inconel 600, a mineral insulation layer, usually MgO or Al_2O_3, and a metallic central wire called the emitter [1]. The emitter is made from a metal, such as vanadium, cobalt or platinum and is typically 1.5 mm in diameter and 0.3 to 1.0 m long. The lead cable is typically 1 mm in diameter and from 6 to 15 m in length, and usually the insulation and sheath material are the same as for the detector. When the detector is placed in the radiation field inside a nuclear reactor and the core wire of the lead cable is connected through an ammeter to the sheath, a current, proportional to the radiation field, will flow. No external bias voltage is required. The impedance of a functioning detector is usually greater than 100 MΩ, making it nearly an ideal current source.

The current induced in the co-axial cable, be it the detector or lead cable, can be attributed to three main causes [2]:

- (n, β) interactions, in which neutron capture in the materials of the detector results in the formation of a radioactive daughter that decays by β-emission,

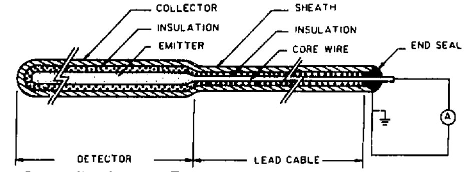

FIGURE 1 SCHEMATIC OF A SELF-POWERED FLUX DETECTOR AND LEAD CABLE

- (n, γ, e) interactions, in which prompt capture γ-rays emitted following neutron capture in the detector liberate free electrons primarily via Compton and photo-electric processes, and
- (γ, e) interactions, in which reactor γ-rays interact in the detector to liberate free electrons.

The (n, γ, e) interaction is prompt, while (n, β) and (γ, e) interactions yield delayed signals. Thus the dynamic response of a detector or lead cable depends on the relative importance of the three current-producing mechanisms. The detector geometry and the presence of fuel or hardware also affect the dynamic response because they affect the relative amplitudes of the three signals.

The established technique[2] to model dynamic response of a flux detector is to fit the signal from a detector following a reactor trip to equations (1) to (3) below.

$$\frac{I(t)}{I(0)} = F_p \frac{\phi(t)}{\phi(0)} + \sum_j \frac{I_j(t)}{I(0)} \qquad (1)$$

$$\frac{dI_j(t)}{dt} = \lambda_i \; I_j(0) \left[\frac{\phi(t)}{\phi(0)} - \frac{I_j(t)}{I_j(0)}\right] \qquad (2)$$

$$A_j = \frac{I_j(0)}{I(0)} \qquad (3)$$

This determines a set of parameters for F_p, the prompt fraction and A_j, the amplitude of the delayed component with decay constant λ_i. Here, $\phi(t)$ is the reactor flux, as measured by a reference fission chamber, $I(t)$ is the flux detector current and $I_j(t)$ is the current due to the jth delayed component. The parameters F_p, A_j, λ_j then define the transfer funtion given by

$$\frac{\Delta\ I(s)}{\Delta\ \phi(s)} = K \left[F_p + \sum_j \frac{\lambda_j\ A_j}{(s+\lambda_j)}\right] \qquad (4)$$

where s is the Laplace transform variable.

The total output current, for detectors of interest, ranges from 100 nA to about 2 μA. The current from a lead cable is usually between 1 and 20 nA. The prompt fraction, F_p, ranges from a low of about 0.05 for vanadium detectors to a high of ≥ 1.0 for Inconel detectors. Up to six decay constants that range in value from 0.25 to 5 x 10^{-7} s^{-1} are used in equation (2) to match a detector's response. The largest decay constant of interest is 10 s^{-1} (a time constant of 100 ms). We would like to determine the prompt fraction and amplitude of delayed components with sufficient accuracy to model the detector current to 1%.

The above range of currents and model parameters are the basis for choosing the method of experimental measurement and many of the data acquisition system's parameters. The method is also constrained by operational requirements at the NRU reactor.

THE EXPERIMENTAL MEASUREMENT OF DYNAMIC RESPONSE

The method used to measure the dynamic response of detectors in NRU is as follows:
- the reactor power level is raised to full power and held steady to allow the detectors to reach equilibrium,
- a fission chamber (a prompt-responding neutron detector) or a self-powered detector with a known dynamic response is placed near the detectors to be studied,
- the reactor is tripped (absorbers dropped into the reactor to quickly reduce power) and the output from the reference fission chamber or flux detector and detectors with the unknown response are recorded,
- the data are continuously recorded as long as the reactor is shut down (a few days).

During the shutdown the reactor flux will fall to about 10^{-2} of its initial value in the first second and to 10^{-4} in about an hour. After all data have been recorded, a computer program is used to fit the recorded data to equations (1), (2) and (3) by adjusting F_p, A_j and λ_j. To determine the amplitudes A_j accurately, the data must be recorded accurately. We have aimed at recording the flux-detector current with an accuracy of 1% of its true value. During the first part of the transient, about 20 readings per second are required from each detector. As the flux begins to decay more slowly, fewer readings are required.

THE DATA ACQUISITION SYSTEM

The basic scheme selected for recording the data from self-powered flux detectors is shown in Figure 2. Each detector is connected to a current-to-voltage amplifier which produces a high-level output voltage from the low-level input current. The voltage is then converted to digital form by an analog-to-digital converter and read into microcomputer memory. The data are then transferred to a disk for storage from which they may be subsequently retrieved for later analysis. The microcomputer and its peripherals, a conventional configuration, are described below. The current-to-voltage amplifiers are intimately tied to the flux detector characteristics and the overall detector-amplifier circuit must be carefully designed to achieve reliable performance.

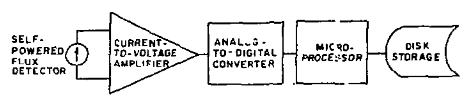

FIGURE 2 DATA ACQUISITION SCHEME

Current-to-Voltage Amplifiers

The desired data from the measurements permit determination of time constants as short as 100 ms and as long as several days. For this reason an amplifier was specified with a bandwidth from D.C. to 16 Hz (a time constant of 10 ms). The measurement of lead cable currents in the order of 1 nA to 1% accuracy requires the leakage current from the amplifier to be less than 10 pA. The measurement of currents to 1% accuracy, as they decrease by a factor of up to 1000 during a transient, requires some form of auto-ranging.

A Keithley Model 18012 amplifier was selected to meet these requirements. A simplified schematic of this amplifier is shown in Figure 3, and a summary of its specifications is given in Table 1[3].

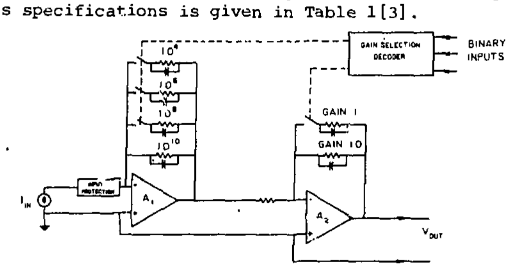

FIGURE 3 SIMPLIFIED SCHEMATIC OF KEITHLEY MODEL 18012 CURRENT-TO-VOLTAGE AMPLIFIER

TABLE 1

SUMMARY OF SPECIFICATIONS FOR KEITHLEY MODEL 18012 CURRENT-TO-VOLTAGE AMPLIFIER

RANGE	±10 V output for $\pm10^{-3}$ A to $\pm10^{-10}$ A input current in decade steps
RANGE SELECTION	3-line binary (TTL logic levels)
RANGE SWITCHING	<2 ms for 10^{-3} A through 10^{-8} A ranges <10 ms for 10^{-9} A and 10^{-10} A ranges
BANDWIDTH	16 Hz for 10^{-3} A through 10^{-8} A ranges and 8 Hz for 10^{-9} and 10^{-10} A ranges with 18 nF of cable capacitance at the input
ZERO DRIFT	±0.5% of full output per week ±0.05% of full output per °C
INPUT OFFSET CURRENT	less than 10^{-11} A
MAXIMUM INPUT OVERLOAD	1000 V from 0.01 μF 30 V continuous 10 mA continuous
MAXIMUM VOLTAGE BURDEN	<5 mV

The model 18012 is a single ended amplifier with one of its 8 gain ranges set by a 3-line binary imput from the microcomputer. An output of ±10 V can be obtained for an input current of from 100 pA to 1 mA.

The low current levels and relatively large bandwidth require very careful attention to shielding and grounding. Unwanted 60 Hz pickups either due to direct capacitive coupling or due to ground loops can easily overwhelm the signal current if care is not taken. Filtering is generally ineffective unless an elaborate high-order filter is used as the required cutoff frequency is only 2 octaves below 60 Hz.

The ground loop current has been eliminated by permitting only one ground point in the flux-detector amplifier circuit, as shown in Figure 3. As a consequence of the metallic outer sheath, the flux detector is likely to be in electrical contact with the reactor structure which is accepted as being at ground potential. To ensure a reliable contact, a deliberate connection is made from the flux-detector sheath to the reactor structure at the outer end of the lead cable. No other ground connections have been permitted. This has been accomplished by

- providing a separate power supply (a DC to DC converter) for each amplifier,
- using optical isolators between the computer and the binary inputs for amplifier gain selection, and
- using a differential multiplexer and analog-to-digital converter to read the output voltage into the computer.

Electrostatic shielding has been given equal consideration. Physical constraints dictated that the amplifier could not conveniently be located closer than 50 m from the end of the detector lead cable. A shielded twisted-pair cable (Belden type 8641) is used to connect each flux detector to its amplifier. Connections at all intermediate junction boxes are shielded to prevent 60 Hz pickup noise. Conventional terminal strips are inadequate because both conductors are exposed and subject to 60 Hz pickup. Care is also taken to ensure that the shield was grounded only at the flux detector, as current flowing in the shield can also couple to the other conductors in the cable. The overall scheme, comprising flux detector, cable, amplifier, power supply and computer connections is shown in Figure 4. The shield is insulated at all points to prevent multiple ground connections and current in the shield.

The amplifiers, as supplied by the manufacturer, are not mounted in a chassis. A package was developed to house five amplifiers, optical isolators and associated power suppliers in a 4-width NIM module[4].

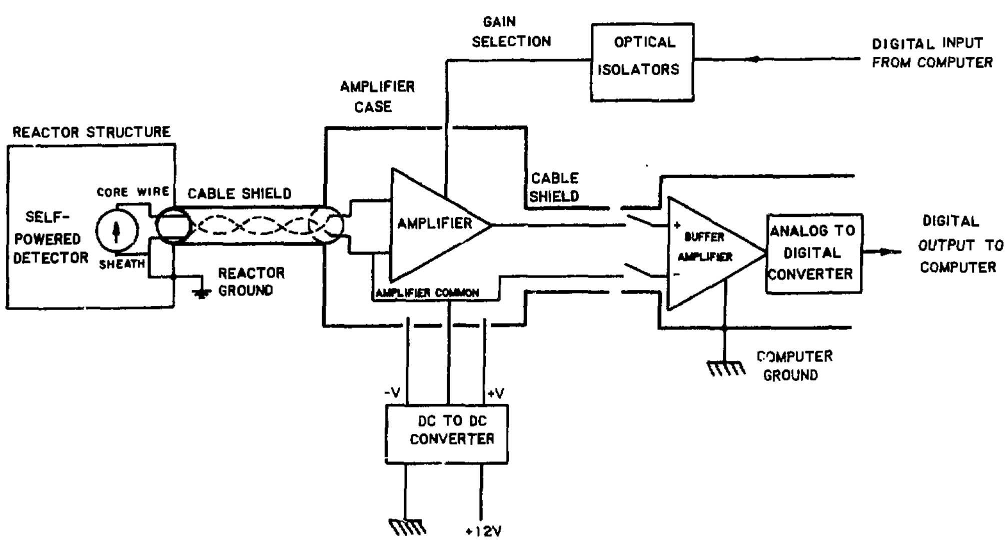

FIGURE 4 GROUND AND ELECTROSTATIC SHIELD CONNECTIONS FOR CURRENT-TO-VOLTAGE AMPLIFIER AND ANALOG-TO-DIGITAL CONVERTER

Power for each amplifier (±15 V) is provided from individual DC to DC converters that in turn draw their power from the ±12 V NIM power supply. The DC to DC converters and optical isolators for the gain selection inputs are mounted on a printed circuit board at the side of the module. The input-current connection to each amplifier is made via a 2-pin Lemo connector, mounted in a Teflon panel at the front of the module. The output connections are made via 2-pin twist lock connectors, also mounted in a Teflon panel, at the rear of the module. The range selection can be controlled either from the microcomputer or a single width NIM module with manual switches, which has also been developed.

To characterize the dynamic response of the amplifier, its frequency response has been measured. The results depend on the input shunt capacitance of the flux detector and interconnecting cable. Figure 5 shows the results obtained for a shunt capacitance of 11.5 nF, the expected average value at the NRU installation. The measurements were made with a length of Belden 8641 cable to obtain the required capacitance. A resistor and voltage source were used to simulate the flux-detector current source.

The frequency response was measured using the pseudo-random binary sequence/fast Fourier transform technique[5]. Five amplifiers were tested on eight ranges for a total of 40 measurements. The results for the 10^{-3} and 10^{-10} A range are shown in Figure 5. The upper gain and phase curves, in Figure 5, are the maximum response for the 10^{-3} A range. The lower gain and phase curves are the minimum response for the 10^{-10} A range. The responses for the other 6 ranges lie between the two responses shown.

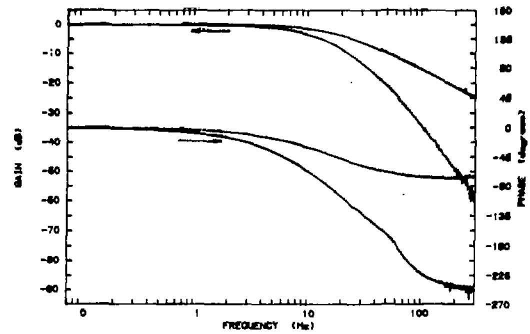

FIGURE 5 FREQUENCY RESPONSE OF KEITHLEY MODEL 18012 AMPLIFIER WITH 11.5 nF SHUNT CAPACITANCE AT THE INPUT

The amplifier output noise, as installed in NRU, has been measured from strip chart recordings. The peak-to-peak noise is

$<5\%$ on the 10^{-10} A range,
$<0.5\%$ on the 10^{-9} A range,
$<0.1\%$ on higher ranges.

These results were obtained with the interconnecting cable installed and open circuit at the reactor end.

Microcomputer System

The microcomputer system, shown in Figure 6, is based on Digital Equipment Corporation's (DEC) LSI-11/23 microcomputer. Data are read from the current-to-voltage amplifiers with a pair of ADAC Corporation model 1014 analog-to-digital converters and model 1012ex 32 channel multiplexers.

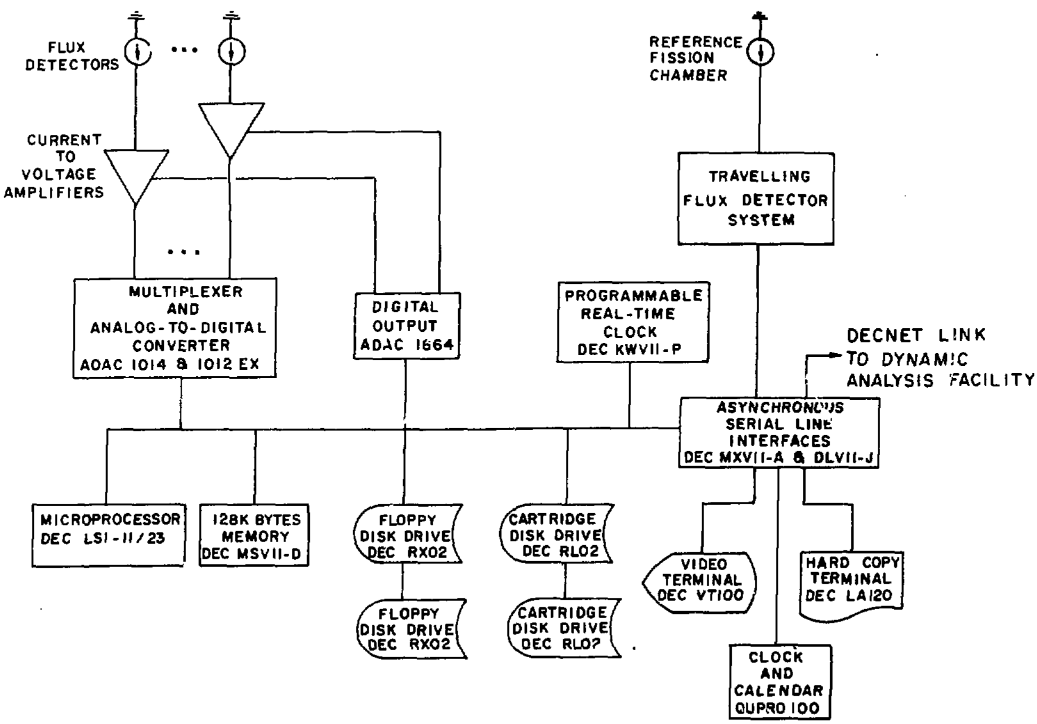

FIGURE 6 MICROCOMPUTER SYSTEM FOR COLLECTING DATA FROM SELF-POWERED FLUX DETECTORS

The model 1014 converter has a ±10 V input with a 13-bit plus sign output to provide a resolution of 1 part in 8192. Two converters have been used in the NRU installation, each with 19 amplifiers, for a total of 38 low-current inputs to the computer. Two ADAC model 1664 digital output modules are used to control the range of the 38 amplifiers.

The scanning rate of the analog-to-digital converters is controlled by a DEC model KWV11-P programmable real-time clock. A scanning interval of 50 ms is set into the clock. When a clock interrupt occurs, the program reads the required outputs from the amplifiers, checks for over- or under-range conditions and then sets digital outputs to bring the amplifier output voltages within the desired range.

Data from the amplifiers are stored in computer memory at a specifiable logging rate. If the logging interval is greater than 1 s, the average values for the previous second are stored. When a block in computer memory is full, the data, time of day and identifiers are written to the RL02 cartridge disk for permanent storage.

The travelling flux detector system[6] is used to position the reference fission chamber and read data from it. The video terminal is used for program development and operator commands to the data logging program. The hard copy terminal provides listings of programs and hard copy of data.

The LSI-11/23 microcomputer system is operated with DEC's RT-11 4.0 operating system[7]. All programs have been written in FORTRAN and compiled with the FORTRAN/RT-11 V 2.5 compiler[8]. Subroutines from ADAC corporation's ADLIB[9] have been used to control the analog-to-digital converters. The date and time-of-day are maintained in a Qupro model 100 clock with its own battery power supply. In the event of power failure and restart, the program reads the time of day and date from the Qupro clock to set the computer's internal clock.

SYSTEM TEST RESULTS

To test the data acquisition system prior to installation at the NRU reactor, a simulation of four flux detectors and a point reactor was implemented on the Dynamic Analysis Facility[10] comprising analog and digital computers. The simulation consisted of

- a point reactor with six delayed-neutron groups,
- a rudimentary control system,
- a function generator to provide the reactivity versus time function of a reactor trip,
- four self-powered flux detectors, each having four delayed-signal components.

The simulation was run to simulate a trip of the NRU reactor. Figures 7 and 8 show strip chart recordings of the reactivity input, reactor flux and the output of the four simulated flux-detectors.

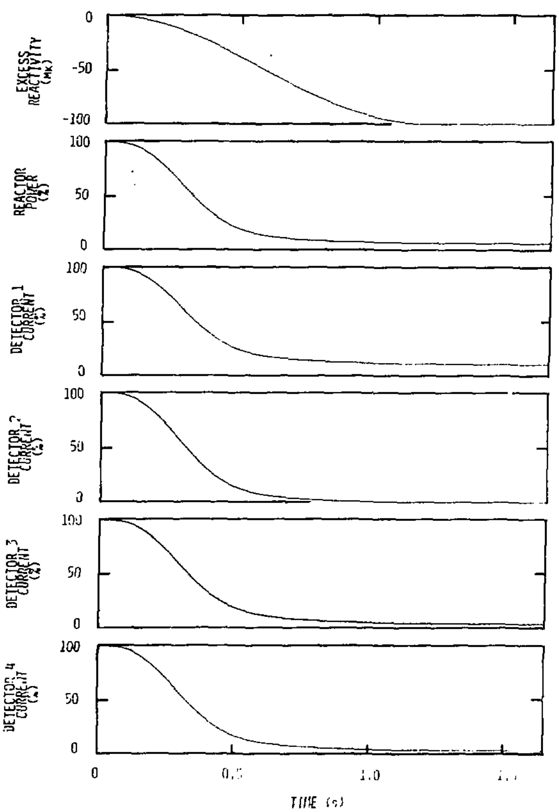

FIGURE 7 SIMULATION OF SELF-POWERED FLUX DETECTORS

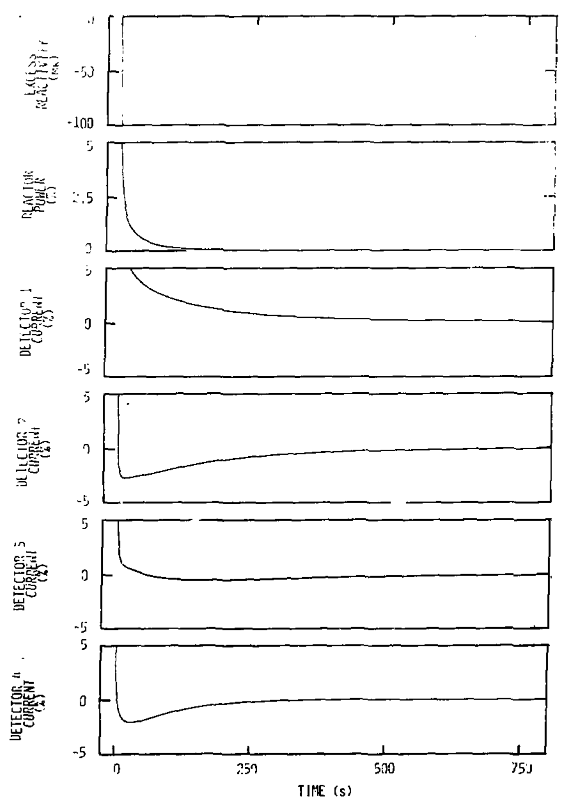

FIGURE 8 SIMULATION OF SELF-POWERED FLUX DETECTORS

Figure 7 shows the variables for the first 1.5 s of the trip transient while Figure 8 shows the same variables for the first 750 s. Note that there is a scale change on the reactor power and detector currents from Figure 7 to Figure 8. The reactor flux (equivalent to the output of the reference fission chamber for a real trip transient) and four flux-detector outputs were recorded by the microcomputer system for 500 s. The sampling intervals used to record the data were

- 50 ms for the first 60 intervals (i.e. 3 s),
- 1 s for the next 60 intervals (60 s),
- 5 s for the next 60 intervals (300 s),
- 20 s for the remainder of the 500 s.

The measured results from the simulation were read into an off-line computer code to extract the prompt and delayed fractions of the simulated detectors. Table 2 gives the known fractions and decay constants along with the same constants determined by measurement and fitting. The decay constants of delayed componts A_1 to A_4 for all detectors are 1.0, 0.1, 10^{-2} and 5×10^{-3} s^{-1} respectively.

TABLE 2

COMPARISON OF KNOWN AND MEASURED SIGNAL COMPONENTS FROM 4 SIMULATED DETECTORS

DETECTOR 1

COMPONENT	KNOWN	MEASURED	% ERROR
F_p	0.92	0.923	+0.33
A_1	0.020	0.017	-15.
A_2	0.020	0.020	0.
A_3	0.020	0.019	-5.
A_4	0.020	0.021	-5.

DETECTOR 2

COMPONENT	KNOWN	MEASURED	% ERROR
F_p	1.08	1.078	-0.19
A_1	-0.020	-0.017	-15.
A_2	-0.020	-0.021	+5.
A_3	-0.020	-0.019	-5.
A_4	-0.020	-0.021	+5.

DETECTOR 3

COMPONENT	KNOWN	MEASURED	% ERROR
F_p	1.00	1.000	0.
A_1	0.020	0.210	5.
A_2	-0.020	-0.210	5.
A_3	0.020	0.020	0.
A_4	-0.020	-0.020	0.

DETECTOR 4

COMPONENT	KNOWN	MEASURED	% ERROR
F_p	1.02	1.020	0.
A_1	0.010	0.010	0.
A_2	0.010	0.010	0.
A_3	-0.050	-0.052	4.
A_4	0.010	+0.012	20.

CONCLUSION

A data acquisition system to measure the low-level current from self-powered detectors has been assembled from commercially available amplifiers and microcomputer components. Careful attention to ground connections and electrostatic shielding has provided a relatively wide bandwidth (8 to 16 Hz) system that has a low noise level. A conventional LSI-11/23 microcomputer data acquisition system, programmed in FORTRAN, provides high speed recording of data, in digital form, from self-powered flux detectors. The overall performance of the data acquisition system and off-line curve-fitting program was tested by

- generating detector signals on an analog computer,
- sampling and storing the signals via the data acquisition system, and
- processing the captured data in an off-line program.

The known and measured results agreed within an acceptable error band.

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