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TITLE PROOF-OF-PRINCIPLE MEASUREMENTS FOR AN NDA-BASED CORE DISCHARGE MONITOR

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PROOF-OF-PRINCIPLE MEASUREMENTS FOR AN NDA-BASED CORE DISCHARGE MONITOR

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ABSTRACT

The feasibility of using nondestructive assay instruments as a core discharge monitor for CANDU reactors was investigated at the Ontario Hydro Bruce Nuclear Generating Station A, Unit 3, in Ontario, Canada. The measurements were made to determine if radiation signatures from discharged irradiated fuel could be measured unambiguously and used to count the number of fuel pushes from a reactor face. Detectors using the (γ,n) reaction thresholds of beryllium and deuterium collected the data, but data from shielded and unshielded ion chambers were collected as well. The detectors were placed on a fueling trolley that carried the fueling machine between the reactors and the central service area. A microprocessor-based electronics system (the GRAND-I, which also resided on the trolley) provided detector biases and preamplifier power and acquired and transferred the data. It was connected by an RS-232 serial link to a lap-top computer adjacent to the fueling control console in the main reactor control room. The lap-top computer collected and archived the data on a 3.5-in. floppy disk. The results clearly showed such an approach to be adaptable as a core discharge monitor.

INTRODUCTION

CANDU reactors are refueled semicontinuously in both directions during operation to control the core reactivity and to use the reactor fuel efficiently. The refueling is carried out by an automated fuel-handling system that moves fresh fuel from a fresh-fuel port at a central storage area to the reactor face by a "charge machine." Fresh fuel is "pushed" into one face of the reactor from the charge machine, and irradiated fuel is simultaneously removed from the other face by a discharge machine. The fuel is then transported back to the central storage area where it is discharged into temporary storage through irradiated fuel ports. A conceptual representation of this is shown in Fig. 1.

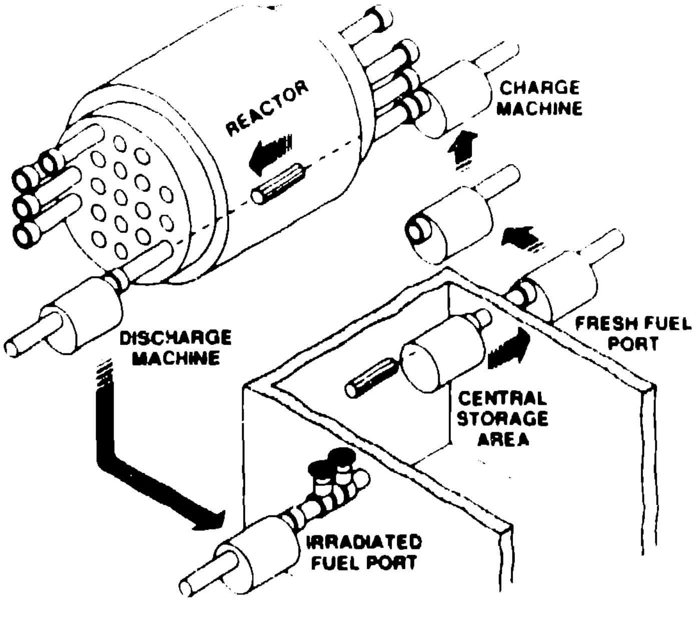

Fig. 1. Conceptual diagram of fueling cycle.

At multi-reactor stations, the charge and discharge fueling machines, which contain fresh or irradiated fuel, are transported on trolleys that move in the tunnels that connect the reactors and the central fuel storage area (CSA). A transverse cross section of the tunnel and the reactor containment is shown in Fig. 2(a). A longitudinal cross section is shown in Fig. 2(b).

A CANDU reactor might discharge between 55 and 65 fuel bundles per week. At some multi-reactor stations, this number is multiplied by the number of reactors. This large number of irradiated fuel assemblies, coupled with the many possible paths for diversion presented by the logistics of transporting the fuel between the various reactors and storage areas, defines the requirements of a safeguards approach. The classical method for safeguarding would require seals and cameras at strategic locations. These efforts could be supplemented by short-notice random inspections (SNRI). Reviewing camera images, verifying seals, and staging SNRI is very human resource intensive. Hence an alternative method of safeguarding the fuel was sought.

An alternative described in this paper uses radiation detectors to monitor the movement of irradiated fuel between the reactor core and a central storage area. The thoughts on this method were prompted by a feasibility study for a reactor power monitor that was done by Bot Engineering Ltd in

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[*] Work was performed while on leave as a United States cost-free expert to the International Atomic Energy Agency.

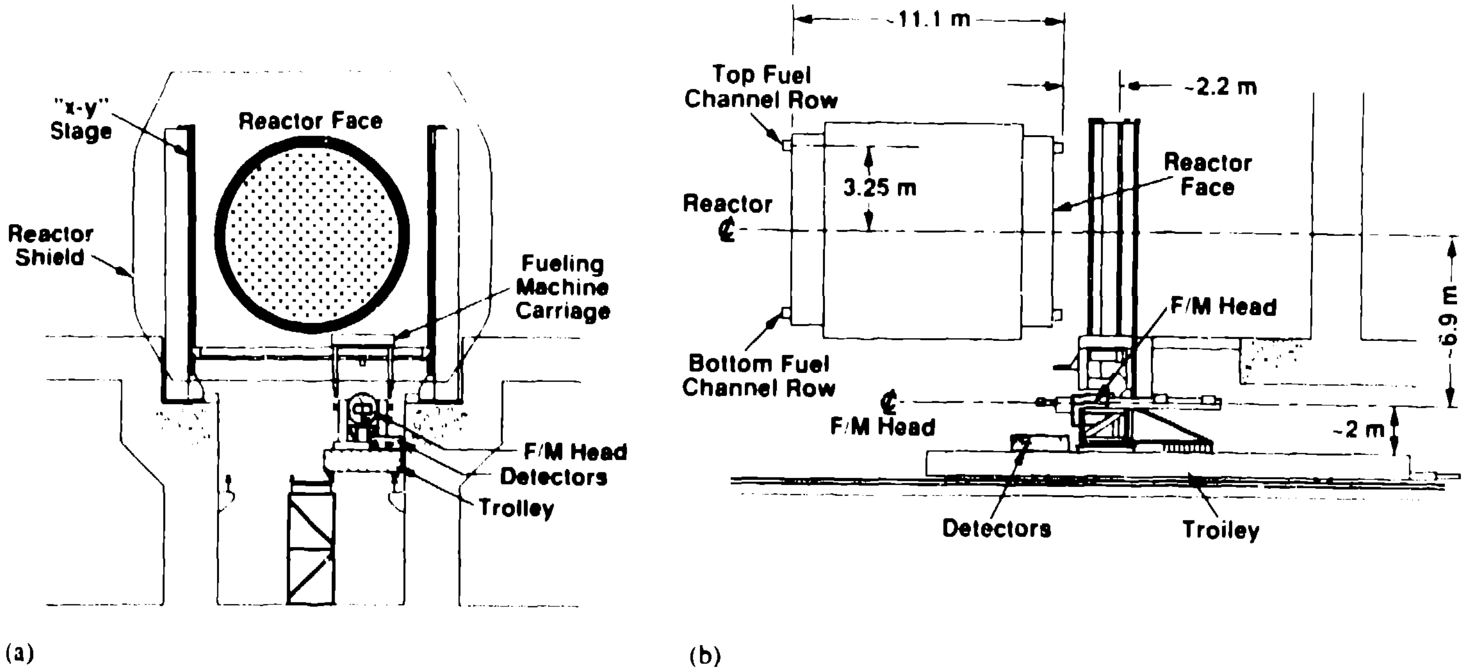

Fig. 2(a). Transverse section of reactor vault and service tunnels. (b) Longitudinal section of reactor vault and service tunnels.

Campbellville, Ontario, Canada. This study reported the detection of high-energy (>7 MeV) gamma rays in the vicinity of the external piping of the reactor heat exchange system. The proof-of-principle (POP) measurements were made to determine if radiation signatures from discharged irradiated fuel could be measured unambiguously and used to count the number of fuel pushes from a reactor face. Detectors using the (γ,n) reaction threshold of beryllium and deuterium collected the primary data, but data from shielded and unshielded ion chambers were collected as well. This work was done during the summer of 1987 at Bruce Nuclear Generating Station (BNGS) A, Unit 3, in Ontario, Canada.

MEASUREMENTS

Physical Layout of Reactor and Trolleys

The layout of the reactor and detectors is shown in Figs. 2(a) and 2(b). The fueling machines are transported by trolleys that travel in the tunnel under the reactors and fuel storage area. During a fueling cycle, the trolleys travel under the reactor and position the fueling machine under the fueling-machine carriage for the fuel-handling machine on the x-y stage. The trolley elevator, on which the fueling machine sits, moves the fueling machine up to the fueling machine carriage. The x-y stage and carriage positions the fueling machine on the ends of the fuel channels.

It should be noted that these activities occur on both ends of the reactor; one for the change fueling machine, the other for the discharge fueling machine.

The fuel channels are horizontal. A map of the channels is shown in Fig. 3. The columns are labeled from 1 to 24, the rows from A to Y with the label I not being used. For our measurements, the detectors were located under column 5. The outer rows and columns are slightly less than 3.4 m from the center line of the reactor. The bed of the trolley is about 9.1 m below the center line of the reactor, and the center line of the top magazine position in the fueling machine is about 2 m above the bed when the fueling machine is traveling on the trolley.

Detectors

The primary detector type chosen for the POP measurements was a (γ,n) threshold detector. One was a Be(γ,n) detector, the other was a D(γ,n) detector. The first was readily available to the International Atomic Energy Agency (IAEA) and had been used both by the IAEA for gathering safeguards data and by Los Alamos National Laboratory during the cleanup at the Three Mile Island Reactor.[1,2] Hence its use was understood. In addition, a D(γ,n) detector was used because of the availability of D_2O at CANDU-type reactors. Both of these detectors produce photoneutrons when gamma rays above 1.6 MeV (2.2 MeV for the latter) interact with the beryllium (deuterium) of the detector. Fission chambers inside the beryllium (deuterium) then detect the created and moderated neutrons. Detectors that use fission chambers are virtually immune to high gamma dose rates and can be used in the presence of a large gamma-ray background. In addition, neutrons are generated only by gamma rays that exceed the reaction threshold; other types of detectors must rely on electronics or very heavy shielding to discriminate against the very large

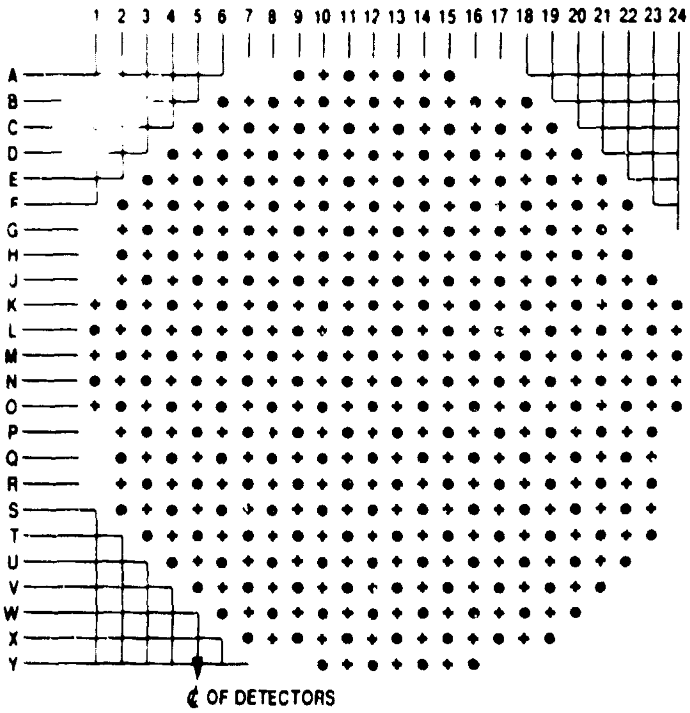

Fig. 3. A core face map of the fueling channels.

amounts of lower energy gamma-ray interference. Both of these methods significantly impact the hardware and the resulting spectra seen by the detectors.

The secondary type of detector was an ionization chamber. There were several reasons for including this type of detector in the POP measurements. First, the electronics used with the fission chambers also supports simultaneous use of the ionization chambers (as in the GRAND-Fork spent-fuel measurement systems). Shielded and unshielded ionization chambers provide additional data that make a monitoring system much harder to fool. Second, the intensity of the high-energy gamma rays that exceed the thresholds of the primary detectors decays rather rapidly. These secondary detectors are sensitive to the gross radiation inside the reactor vault long after shutdown of the reactor.

An attractive feature of both the fission and ionization chambers is that they are very dependable and require a minimum amount of auxiliary equipment. They should require very little maintenance and no adjustment during 20 years of operation.

Electronics

The electronics package used for the POP measurements was the commercial version of ion and neutron detector electronics (ION-1)[3] developed at the Los Alamos National Laboratory for use with a spent-fuel measurement fork detector. The commercial electronics package,* which is called the GRAND (Gamma Ray And Neutron Detector electronics package), is a microprocessor-based electronics system. It provided biases for the fission chamber and ionization chambers, preamplifier power for the fission chamber, and data acquisition and transfer. A GRAND has internal batteries that allow it to operate for more than 24 h if ac power is lost.

The Measurement System

The measurement system continuously made 10-s data acquisitions during its operation. The data from one threshold detector and one ionization detector, and information on the setup and performance of the GRAND, were transferred by the GRAND's serial port to a computer after each acquisition, and then a new acquisition was started. All of this was accomplished by the GRAND's resident firmware.

To assure the necessary performance, the detectors could not be separated by more than 10 m from the GRAND electronics. Hence a 3000-lb (1365-kg) lead shield was built for the GRAND so that it could be placed on the fueling trolley next to the detectors. [The placement of the detectors is shown in Figs. 2(a) and 2(b)]. The GRAND and detectors ran unattended for 5 weeks.

The computer was set up adjacent to the refueling console in the main reactor control room. The battery-backed computer, a Toshiba 1100, received this data, stored it on a 3.5-in., 0.7-Mbyte floppy disk, and displayed the last 24 records received. The data were transmitted over lines supplied by the facility using industrial modems.

Data were collected at a rate of approximately 750 kbytes/day. These data were retrieved and taken to an off-line Toshiba 2100 computer for treatment and review using the Symphony spreadsheet program. The detector information was extracted and put into a large spreadsheet that was only limited by the memory of the Toshiba. The time periods of interest were plotted for review. Analysis with a turnaround time of only 2-4 h after obtaining the disks allowed questions to be asked of the fueling operator and plans to be made for the next fueling cycle. Hence, unresolved questions could be answered during the next fueling cycle with the close cooperation of the fueling operators.

RESULTS

Going into the measurements, we had not received firm estimates of the radiation levels we would see. We were lucky that the detector sensitivities matched the radiation levels very well. (See Fig. 4.)

Figure 4 shows the activities observed by the Be(γ,n) detector as it entered the reactor vault just after time 0 on the plot. The background signal is approximately 1300 counts/s. The fueling machines removed the end and shield plugs from the channel to be refueled. This activity is not seen by the detector. Just before 4000 s, the first push (push equals two bundles discharged from the core) took place. One observes a

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*Commercially available from DS Davidson Co., 19 Barnhard Rd., North Haven, Connecticut, USA.

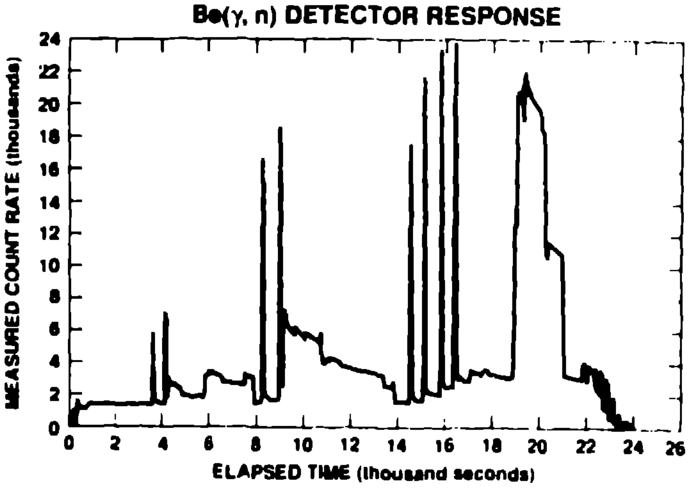

Fig. 4. A complete fuel campaign as detected by the Be(γ,n).

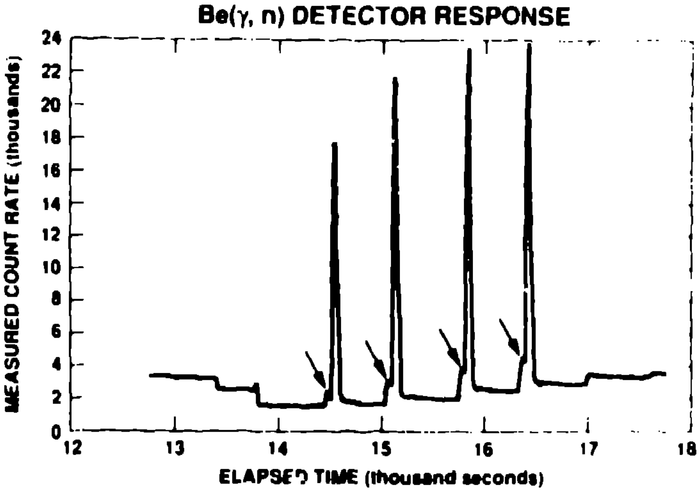

Fig. 5. Leading-edge bumps on response peak.

continuum. Nine minutes after the first push a second one occurs with a peak of approximately 6800 counts/s. These two pushes were from channel C-09, which was approximately 15 m from the detectors. At this reactor, the bundles are pushed in pairs. The second peak is larger because those bundles were closer to the center of the reactor and hence they were exposed to a higher neutron flux.

The structure of the data after the second push and up to 8000 s is indicative of the motions of the discharge machine as it rotates to put the shield and end plugs back into the fuel channel. The x-y stage then transports the fueling machine magazine to the next channel to be fueled. The decay of the radiation from the stationary discharge machine can be observed during the time it is stationary. The high and low excursions before the third push are due to the rotations of the fueling machine magazine to remove end and shield plugs and position an empty chamber to receive the fuel from the next push. The next two pushes occurred just after 8000 s. These pushes were from channel V-11, which is significantly closer to the detectors: approximately 11 m from the detectors. The rotations of the magazine and translations of the discharge machine and the decay of the radiations from the fuel inside the machine are again clearly visible on the response curve as the discharge machine is moved to position X-19 for four pushes. On these pushes, little bumps are visible on the leading edges of the response peaks (Fig 5). These bumps are indicative of the fueling procedure by which the assemblies are pulled slightly and then pushed back to assure that they have been secured. Here the unequal core flux effect on the activities of the bundles is clearly visible in the relative heights of the peaks. When the fueling machine is full, the continuum is significantly higher. The fueling activities in the vault lasted about 4 h.

At about 19 000 s, a large signal excursion was noted. With the help of the fuel-handling personnel, the mystery of this monolith was explained as follows. The first large excursion is due to the x-y stage bringing the discharge machine down to the elevator on the fueling trolley. The delay at about the mid-height point results from the discharge machine being transferred from the x-y stage to the elevator. The elevator then brought the discharge machine down to the trolley bed where the machine was repositioned. Once the machine was in position on the trolley, the trolley traveled (carrying both the discharge machine and the detectors) to the CSA. The decay of the radiation during the travel is clearly visible. The fueling machine was between 1 and 3 m from the detectors during the trip. The process of moving the fueling machine from the trolley to the x-y stage at the CSA and then to the spent-fuel port is reversed from the process in the vault. Note that the x-y stage sat for a while before carrying the discharge machine to the port. This produces the decay visible on the falling edge of the monolith. A further decay can be seen before the fuel was pushed into the spent-fuel port. The signature of the transfer of the irradiated fuel into the storage areas is shown better in Fig. 6.

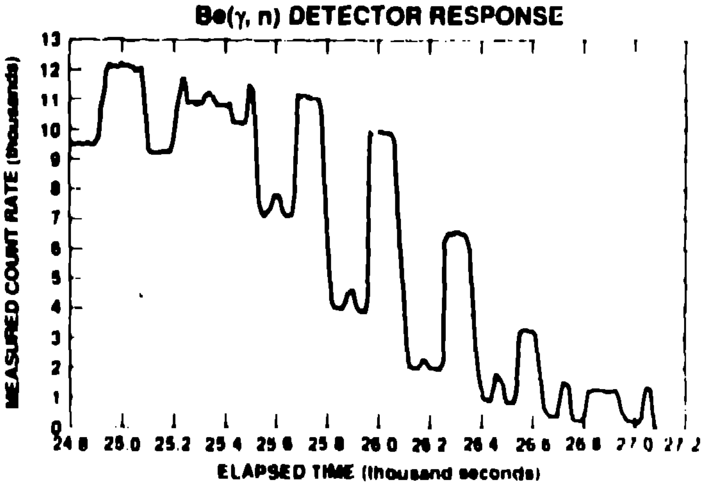

Fig. 6. Signature of irradiated fuel transfer to the central storage area.

This figure was also interpreted with the help of the fuel-handling operators. The first push into temporary storage is the small dome on top of the first monolith. The second push is the slightly bigger bump in the middle of the second monolith. This fuel had been in the fueling machine about 5 h. The monoliths are due to the rotation of the magazine. The rest of the pushes are identified as the bumps between the monoliths. After the last push the continuum falls to 0 counts/s.

Figure 7 shows a shielded ion chamber's view of a fueling campaign. Here one can see structure similar to that of the data from the Be(γ,n) detector except for the actual fuel-push peaks. Similar plots for the unshielded ion chamber show both the structure and the peaks. Each detector produces different fueling-machine-on-trolley radiation levels to background-in-the-vault levels, as well as different peak-to-continuum ratios, which indicates that the detectors are sensitive to different types of radiations and to different regions of spectra of the gamma radiations.

Data also were acquired to check on the half-lives of the radiations being measured. Three distinct groups of radiations with half-lives of 74.8 min, 15.9 min, and 51.8 s were identified. Whereas there are certainly shorter half-life radiations, we were not able to resolve them because of our 10- to 11-s counting cycle period. The fit to the 51.8-s data after the 15.9-min data had been stripped is shown in Fig. 8.

Data similar to that obtained with the Be(γ,n) detector were collected with the D(γ,n) detector. The peak-to-continuum ratios are similar. It also was of interest that many, but not all, of the fuel pushes on the opposite face of the reactor could be seen by the detectors. However, the signals were only slightly above background.

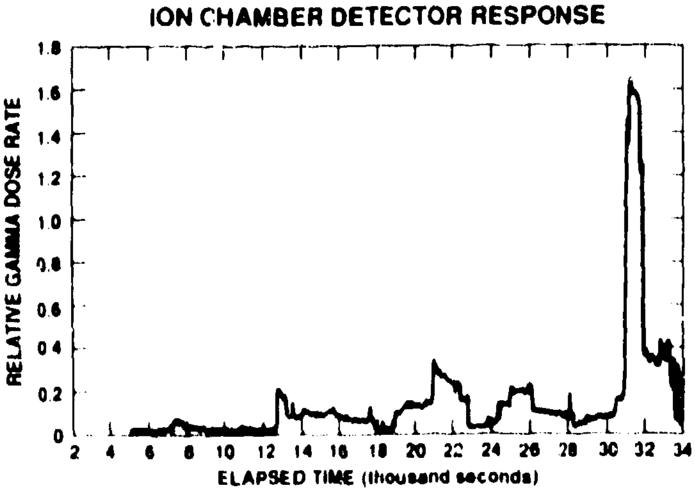

Fig. 7. A complete fuel campaign as detected by a shielded ion chamber.

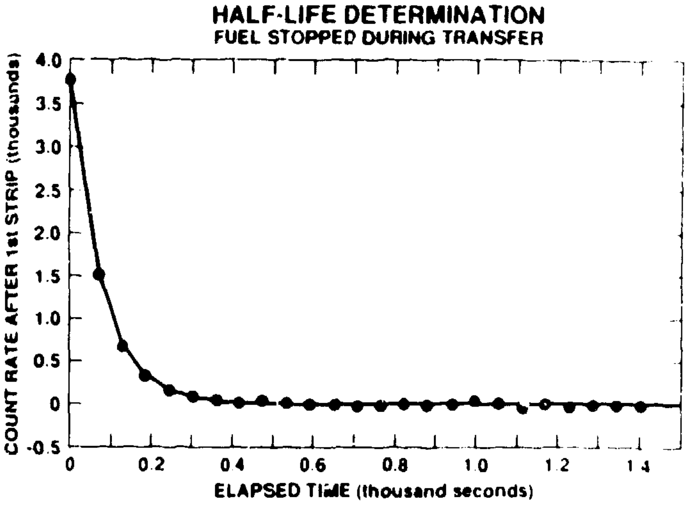

Fig. 8. Half-life data fit.

CONCLUSIONS

From these data, we concluded that the Be(γ,n), D(γ,n), and bare ion chamber detectors were clearly able to detect not only fuel pushes, but also activities unique to the fueling activities in the vault. They also could monitor the transport of the fuel up to its discharge into the temporary storage area for at least 5 to 7 h after the first fuel was pushed into the fueling machine. The shielded ion-chamber data did not show the fuel-push peaks, but did show the rest of the fueling activity signatures. The peak-to-continuum ratios for all cases ranged between 3 and 9.

The half-life measurements showed the detectors to be measuring fuel-specific radiations and not modulations in cesium or cobalt radiations from some unknown physical activity.

One could not conclude from the data that the signal from the threshold detectors comes uniquely from (γ,n) interactions in the detector because these detectors are also sensitive to other neutron activities within the reactor vault. From preliminary conversations with IAEA people knowledgeable about CANDU reactors, it was assumed that the neutron flux in the vault as a result of fuel being pushed was very low. As discussed elsewhere,[4] this may not be the case.

Independent of the actual source of the detected neutrons, the signals *definitely* originate from the discharge of fuel from the reactor. The (γ,n) signals in conjunction with the gross gamma signals when reviewed for peaks and characteristic fueling activity structure are clearly usable to monitor fuel discharged from the core. Hence the detectors and electronics can be effectively used as a core discharge monitor.

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It would have been practically impossible to undertake the feasibility study without the willing cooperation of the Ontario Hydro staff in the Central Maintenance Facility (CMF) at Bruce. We did a substantial amount of preparatory work at CMF.

Special thanks are due to Mr. John Cho at CMF who assisted with preparations for the lead castle to protect the electronics, detector cladding and bagging, transport arrangements, and other logistics. In a similar vein, Mr. Terry Maggs provided invaluable guidance and help at BNGS A.

The success of this measurement campaign also was helped by the extraordinary cooperation of BNGS fuel-handling staff who provided us with accurate data on the fueling activities and consultations as to how their activities correlated to our data. We thank the Canadian Safeguards Support Program to the IAEA and the Canadian Atomic Energy Control Board for supporting the activities and arranging access to the reactor for these measurements.

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