Radiation Measurement of a Operational CANDU Reactor Fuel Handling Machine using Semiconductor Sensors (ICCAS 2003)

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Abstract In this paper, we measured the radiation dose of a fuel handling machine of the CANDU type Wolsong nuclear reactor directly during operation, in spite of the high radiation level. In this paper we will describe the sensor development, measurement techniques, and results of our study. For this study, we used specially developed semiconductor sensors and matching dosimetry techniques for the mixed radiation field. MOSFET dosimeters with a thin oxide, that are tuned to a high dose, were used to measure the ionizing radiation dose. Silicon diode dosimeters with an optimum area to thickness ratio were used for the radiation damage measurements. The sensors are able to distinguish neutrons from gamma/X-rays. To measure the radiation dose, electronic sensor modules were installed on two locations of the fuel handling machine. The measurements were performed throughout one reactor maintenance cycle. The resultant annual cumulative dose of gamma/X-rays on the two spots of the fuel handling machine were 18.47 Mrad and 76.50 Mrad, and those of the neutrons were 17.51 krad and 60.67 krad. The measured radiation level is high enough to degrade certain cable insulation materials that may result in electrical insulation failure.

Keywords: semiconductor, radiation, nuclear, neutron, fuel handling machine, gamma-ray

1. INTRODUCTION

Wolseong Nuclear Power Plant (NPP) is a CANDU type, in which a specific amount of nuclear fuel is continually changed at certain intervals for a cycle of on operation. Fuel handling machine that is situated at the repair room outside the shielding door gets into the front part of the Calendria and exchanges the spent fuels with new ones. Two on-power fuel handling machines installed on both sides of the Calendria simultaneously insert new fuel assemblies and withdraw spent ones into its magazine. The machines move back to the repair room and finish the fuel change process by discharging the spent fuel through the fuel outlet. This process is repeated during a cycle of an operation. The fuel handling machine is composed of a fueling machine head that contains and transports nuclear fuel, a cable loop (Catenary Loop) and a cable trolley (Catenary Trolley). Of them, a total of 34 lines which constitutes the cable loop supply power (10 lines), oil (12 lines) and heavy water (12 lines).

Because the fuel handling machine performs its operations in close vicinity to the on-power reactor and also directly handles highly-radioactive spent fuels, it is exposed to an extremely high level of radiation. Particularly, cable loops in the machine are considered to be the most vulnerable to radiation among all the parts and consequently the cable loops are replaced periodically. It is because, if the cable loop is damaged by high irradiation, it may have serious influences on the safety of the nuclear power station such as the leakage of high radioactive heavy water.

However, if the cable loop is changed much earlier than its lifetime, it is a big loss economically. In addition, considering that a cable loop is an expensive imported goods, it is desirable to fully utilize to its full life span for radiation. The optimal time to change the cable loops of the machine can be determined by comparing their radiation exposure with their radiation tolerance if it is possible to measure the radiation dose of the very expensive fuel handling machine in operation. The actual dose measurement should be able to contribute to the safety enhancement and economic operation of the reactor. However, it is impossible to get the actual measurements of radiation the dose of a fuel handling machine, and it is not easy to get close to the work environment for measurement because of a high level of radiation.

With this background, we measured the radiation dose of a fuel handling machine directly during operation, in spite of the high radiation level. In this paper we will describe the sensor development, measurement techniques, and results of our study. For this study, we used specially developed semiconductor sensors and matching dosimetry techniques for the mixed radiation field. MOSFET dosimeters with a thin oxide, that are tuned to a high dose, were used to measure the ionizing radiation dose. Silicon diode dosimeters with an optimum area to thickness ratio were used for the radiation damage measurements. The sensors are able to distinguish neutrons (which destroys matters) from gamma/X-rays (which mainly ionizes matter with very little destruction).

To measure the radiation dose, electronic sensor modules were installed on two locations of the fuel handling machine. The measurements were performed throughout one reactor maintenance cycle.

2. SEMICONDUCTOR RADIATION SENSOR

2.1 Radiation Measuring using semiconductor

The As for radiation sensors suitable for the hot and humid environments of a CANDU type reactor and also being attached to a fuel handling machine, semiconductor type sensors were adopted. Semiconductor radiation detectors have many advantages in sealing and waterproofing and for the manufacturing of a small-sized sensor module. The PIN diode devices manufactured by us were used for measuring the fast neutron, and pMOSFET (p-type Metal Oxide Semiconductor Field Effect Transistor) of NMRC was used for measuring the gamma rays. Because the two types of devices memorize the radiation dose within themselves, they have merits for measuring accumulative doses without adding external circuits. The radiation characteristics of each device and the measuring principle of them are as follows.

2.2.1 Ionization radiation with MOSFET

MOSFET in the form of Figure 1, a kind of semiconductor device mainly used in switching and amplifying, is controlled by a bias voltage on the gate, which is insulated by an oxide layer (SiO_2). If a pMOSFET is exposed to radiation, electron-hole pairs are formed inside the gate oxide layer of the device. Electrons move fast towards the biased gate and gather around the gate electrode while holes combine with oxide inside the layer, forming semi-permanent positive charges. Because such a hole trap and interface trap function as positive electric fields, it is necessary to bias the additional voltage as much as the newly formed electric fields to operate the device. That is, as the radiation dose accumulated in the pMOSFET increases, the bias voltage at the gate should be incremented to operate it. So, this V_T can be a parameter for measuring the dose of ionizing radiation. For the output characteristic (V_G-I_D) of pMOSFET, the characteristic curves shift rightward with the increase of accumulated radiation dose.

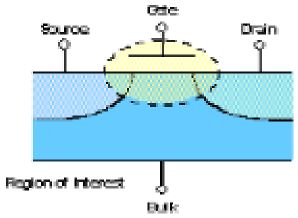


Fig. 1 Configuration of pMOSFET

Among various ways to extract the threshold voltage, the constant current method is advantageous for implementation with small-sized electronic circuits. The method biases a low fixed drain current (I_{ds}) determined through an experiment and obtains the gate voltage. At that time, the formula of the drain current is expressed as in Equation 1,

$$I_d = \mu_n \frac{W}{L} C_{ox}\left[(V_g - V_T)V_d - 0.5V_d^2\right]_d \qquad (1)$$

Here, I_d is the Drain Current, μ_n is the mobility of electron, W is the width of channel, L is the length of channel, C_{ox} is the thickness of oxide layer, V_g is the gate voltage, V_T is the threshold voltage, and V_d is the drain bias voltage.

To use MOSFET-typed radiation sensors properly, it is necessary to consider the radiation sensitivity and the range of applicable total dose according to the application area and the usages[1],[2]

2.1.2 Fast Neutron with PIN diode

When a silicon (Si) PIN diode is exposed to neutrons with a certain level of energy, ionization and displacement damage occur simultaneously inside it. The damage cause the generation of defects in the form of vacancies and interstitials inside it according to the displacement of the silicon lattice resulting from the collision between the neutrons and the silicon lattice (Fig. 2). This displacement damage effect is semi-permanent.[3]

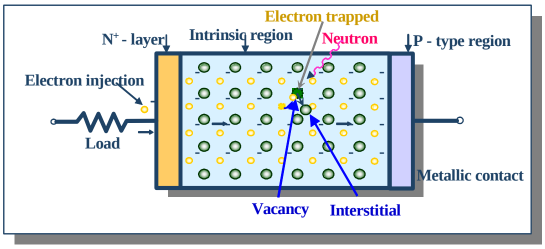


Fig. 2 Displacement damage effect inside PIN diode caused by neutron irradiation

Irrecoverable defects inside the silicon PIN diode increase with the dose of neutron irradiation and function as the centers for the recombination of the internal electric charges moving along the electric fields outside the diode. Finally they cause the decrease in the lifetime of the minority carriers injected into the depletion region. The relation between the increase of neutron dose and the reduction of minority carrier lifetime is as follows.[4],[5]

$$\frac{1}{\tau} - \frac{1}{\tau_0} = \frac{\varphi}{K_r} \qquad (2)$$

Here, τ is the initial carrier lifetime, τ_0 is the carrier lifetime after neutron irradiation, φ is the neutron fluence, and K_r is the damage constant in the base region. The density distribution of the carriers injected into the depletion region is the function of the base width and diffusion length, as neutron irradiation reduces the carrier lifetime and the length of diffusion.

$$L = \sqrt{D\tau} \qquad (3)$$

$$V_D \propto \left(\frac{W}{L}\right)^2 \qquad (4)$$

Here, L is the ambipolar diffusion length, D is the diffusion constant, W is the base width, and V_D is the biased voltage of the PIN diode. In addition, because the external voltage of the PIN diode is expressed as a proportional relation as in Equation (4), the neutron fluence in Equation (1) above is inversely proportional to the charge lifetime of the carrier in the device, and the voltage of the PIN diode indicated by is inversely proportional to the carrier lifetime from the relation of the diffusion length and Equation (2). Consequently, the V_D is proportional to the neutron fluence.

2.2 Radiation calibration function

Doses were calculated by applying a calibration function that were derived from experiments in NIST in the U.S. and gamma ray characteristic sensitivity functions provided by NMRC to each device.

2.2.1 Gamma/X ray dose calibration

For gamma/X ray measurement a 400nm-implanted pMOSFET made by NMRC was adopted. The radiation induced shifts in VT versus an increasing absorbed dose and the line fitted function for Co-60 gamma rays provided by NMRC are in Figure 3.[6]

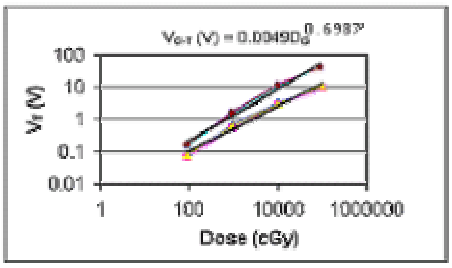


Fig. 3 Radiation induced VT shift of the pMOSFET and a line fitted equation

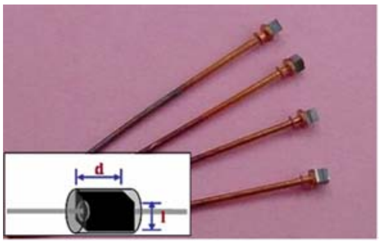
For high sensitive measuring, a voltage of 5V can be biased to the gate of the pMOSFET. But in such a high radiation area as around the fuel-handling machine, no bias state is preferable. The relational function between the accumulated dose of the gamma/X rays with no bias and the threshold voltage of the pMOSFET is as in Equation 5.

$$\Delta V_{G-T} = 0.0049 \times {}_G D^{0.6987} \tag{5}$$

Here, ΔV_{G-T} is the threshold voltage difference of a pMOSFET induced by radiation, and ${}_G D$ is the absorbed dose in the pMOSFET.

2.2.2 Fast neutron dose calibration

For the measurement of the fast neutron dose in real time we manufactured discrete PIN diodes through a fabrication process using a 1.2mm thick (d) high-purity wafer, which resistance was 3,000Ω · cm and the length (l) of a side of the cross section was 1mm, as shown in Figure 4(a). The shape of the manufactured device is found in Figure 4(b).[7]



(a) Inside structure

(b) Appearance of PIN diodes

Fig. 4 Manufactured PIN diodes

Because the energy distribution of the fission neutron emitted from a nuclear reactor is similar to that of the Cf-252, the PIN diodes were irradiated at a Cf-252 national standard source at the US National Institute of Standards and Technology (NIST). The NIST Californium Neutron Irradiation Facility provided spontaneous fission neutron from Cf-252 decay.[8] The diodes were mounted on thin aluminum disks and held in place by aluminum tape. The dose was delivered in six separate irradiations over the course of two days. To prevent an annealing effect, measurement was performed immediately after the irradiation was complete. The neutron activity of the source at that time was 2.435 x 10^9 /cm^2/s. The mean 'neutron fluence' to 'charged particle dose' conversion factor for Cf-252 is 3.1 x 10^{-11} Gy · cm^2. The irradiation geometry is shown in Figure 5. The average distance from the center of the source to the approximate center of a diode is 4.34 cm. Hence the dose rate per irradiation was 1.15 Gy/h. The six separate irradiations are summarized in Table 1.

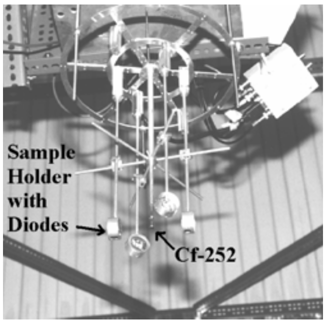


Fig. 5 PIN diodes mounted on four cans facing a Cf-252 fission neutron source (center) for irradiation at NIST.

Table 1 Irradiations at NIST

Irradiations	Duration (h)	Irradiation Dose (rad)	Total Dose (rad)
1	2.218	255	255
2	1.549	178	433
3	1.281	147	580
4	1.186	136	716
5	1.211	139	855
6	1.518	175	1,030

Figure 6 shows the radiation performance of the PIN diodes in a Cf-252 fission neutron environment at the NIST. Results show an excellent linearity with neutron dose. The diode sensitivity to neutron dose was 14.63+0.13 mV/rad based on the fission neutron dose given by the NIST as described above.

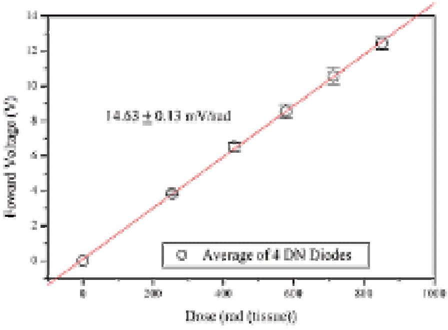


Fig. 6 PIN diodes performance in a Cf-252 fission neutron environment at NIST

2.3 Manufacturing a realtime dosimeter modules

As shown in Figure 7 the two sets of sensor modules to be attached to the nuclear fuel handling machine were manufactured. On each module, four PIN diodes to measure neutron and three pMOSFETs to measure gamma/X rays were installed. In addition the module was waterproofed with a case made of thin material to minimize the radiation shielding.

To obtain accurate information about the irradiation, it is necessary to measure the irradiation dose of the sensor modules in the field immediately after the irradiation. The electronic dosimeter module manufactured as in Figure 8 can get the dose information from the sensors in real-time. The module implemented with PIC16F873 was designed so that a digital constant current pulse of 10mA and 10μA could be biased to the proper terminals of the PIN diodes and pMOSFETs respectively. It has functions to calculate the accumulative dose of the gamma/X ray and neutron respectively from the voltages of the sensors and display them on a small built-in LCD. In addition the module was sealed in a plastic case for long, safe and convenient use in the humid field.

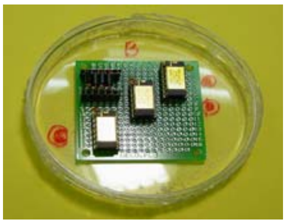


Fig. 7 Radiation sensor module

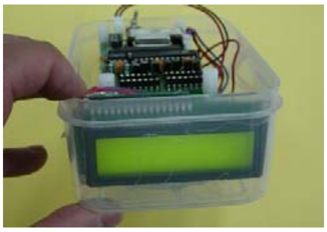


Fig. 8 Dosimetry module for real-time measurement

3. Measuring the radiation upon fuel handling machines

3.1 Measuring method and procedure

Radiation accumulated upon a fuel handling machine comes from the front part of the Calendria due to fission reaction and from the spent fuel withdrawn from the reactor to a magazine. Because it is possible to predict the ultimate cumulative dose of irradiation upon the fuel handling machine by measuring the radiation emitted from the two spots using two sensor modules, one ('A') of them was installed on the upper part of the snout of the machine head for the detection of the radiation from the Calendria, and the other ('B') was attached outside of the magazine. Figure 9 shows the relative locations of the sensors in a fuel-handling machine, and the rightward arrow indicate the sensor module for the Calendria.

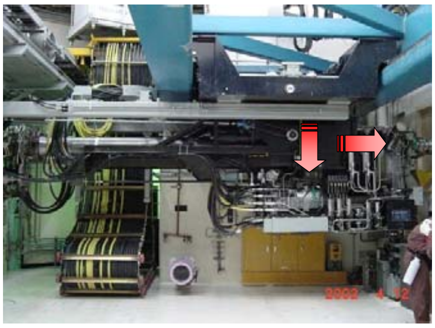


Fig. 9 Two sensor modules installed on fuel handling machine

A fuel-handling machine with sensor modules performs a round of fuel exchanges in which eight of the 12 bundles of fuel rods inside a fuel tube were changed. This work is repeated 625 times a year. The installed sensors are irradiated with high-level radiation from the Calendria and from the withdrawn spent fuel. After the machine returns to the repair room, the sensor modules are removed and measured for the accumulated radiation dose information on them using a developed dosimetry module.

3.2 Results and Analysis

Table 3 and 4 show changes in the characteristic of the devices measured in the field using a dosimeter module on the two sensor modules A and B, which were removed from a fuel handling machine after a round of fuel exchanges

Table 2 Measurements at sensor module A

	$V_{T0\,(Avg.)}$ (V)	$V_{T1\,(Avg.)}$ (V)	$\Delta V_{T\,(Avg.)}$ (V)
PIN Diode	4.68	5.09	0.41
pMOSFET	2.49	7.94	5.45

Table 3 Measurements at sensor module B

	$V_{T0\,(Avg.)}$ (V)	$V_{T1\,(Avg.)}$ (V)	$\Delta V_{T\,(Avg.)}$ (V)
PIN Diode	4.75	6.17	1.42
pMOSFET	2.44	17.15	14.71

The irradiated accumulation dose corresponding to the characteristic changes of these sensors can be obtained by applying a function derived from the sensitivity experiment regarding the NMRC MOSFET and the PIN diode.

3.2.1 Gamma/X ray dosage

By inserting the measured threshold voltage difference (ΔV_T) of Table 2 to Equation 5, the accumulative gamma/X rays dose irradiated on the fuel handling machine for a round of fuel exchanges can be acquired as 29.55 krad and 122.40

krad respectively. As such a work is repeated 625 times a year, so the estimated total doses of gamma/X rays are 18.47 Mrad and 76.50 Mrad respectively.

Table 4 Accumulated gamma/X ray dose at two spots of fuel handling machine

Installed spots of sensor module	A	B
ΔV_T (V) of pMOSFET	5.45	14.71
Accumulated Dosage (krad) / 1 round	29.55	122.40
Accumulated Dosage (Mrad) / 1 year	18.47	76.50

3.2.2 Fast neutron dosage

Because the shift voltages of the PIN diode by neutron irradiation are measured as 0.41V and 1.42V respectively, the accumulated neutron doses on the sensor can be calculated as 28.02 rad and 97.06 rad respectively by applying the sensitivity obtained from the NIST experiment. And as shown in Table 5, the annual neutron dose at each spot will be 17.51 krad and 60.66 krad respectively.

Table 5 Accumulated fast neutron dose at two spots of fuel handling machine

Installed spots of sensor module	A	B
ΔV (V) of PIN diodes	0.41	1.42
Accumulated Dosage (rad) / 1 round	28.02	97.06
Accumulated Dosage (krad) / 1 year	17.51	60.66

If the special structure around the Calendria, the attenuation characteristic of radiation, the physical property of the fuel handling machine are considered with regard to the annual doses of irradiation obtained from this experiment, findings in this experiment will be utilized as important materials in determining a point to change for the cable loop of a fuel handling machine optimal in terms of both economic efficiency and safety.

4. Conclusions and future plans

The paper is the first trial in Korea to measure the dose of irradiation upon a fuel-handling machine in operation in a CANDU typed nuclear power plant. For the measurement, we used self-developed small-sized semiconductor sensor and dosmetry modules. In addition, this was the first trial for distinguishing the neutron that destroys matter from gamma/X-rays that mainly ionize matters and destroys them partially where these types of radiation are mixed. To measure the dose of irradiation upon the fuel-handling machine, sensor modules were attached to two spots of it and the gamma/X-rays and fast neutron irradiated during a round of nuclear fuel exchanges were measured by an offline method.

According to the results of the analyzing measurement in the experiment, the annual cumulative dose of gamma/X-rays on the two spots of head of the fuel-handling machine were 18.47 Mrad and 76.50 Mrad respectively, and those of the neutrons were 17.51 krad and 60.67 krad respectively. The measured radiation level is high enough to degrade certain cable insulation materials that may result in electrical insulation failure. This experiment is one recommended for field application in nuclear power plants in Canada.[9] It is considered necessary to carry out research on monitoring the level of radiation in all the parts of a nuclear reactor to improve the safety of the equipments around the reactors in CANDU type nuclear power plants, which are exposed to intensive radiation during their operation.

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