LOW-COST, LOW-POWER SENSORS FOR MONITORING CANDU REACTOR WASTE IN DRY STORAGE SILOS

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ABSTRACT

Canadian deuterium-uranium (CANDU) reactors are of significant interest because they offer the ability to use natural uranium as a fuel, greatly enhancing the accessibility of nuclear power. The spent fuel, which contains both uranium and plutonium, requires continuous accountability. As reactor storage pools reach their storage capacity limits, it is necessary to periodically transfer the spent fuel to external dry storage silos for long-term storage. Once the fuel is in the silos, it is sealed in place, and a scan of the radiation profile of the silo (via verification tubes running down the length of the silos) is recorded. Subsequent scans of the radiation profile are the primary means for verifying the presence and positions of the stored fuel containers. A means for cost-effective in-situ monitoring would greatly enhance the ability to safeguard the materials. A sensor system for in-situ monitoring of CANDU dry storage silos has been developed and demonstrated. It relies on simple, low-power, inexpensive detectors and electronics. A three-detector system has been shown to be capable of monitoring the status of the fuel at the top and bottom of a storage silo while reliably indicating the direction of movement of fuel into or out of the silo. As an additional feature, the three sensors incorporate a highly sensitive motion-sensing feature that prevents any undetected tampering with the sensors themselves. Once installed in the silos, the sensors are extremely stable, responding only to changes in radiation level. However, any attempt to remove the sensors will result in a large anomalous signal fluctuation that cannot occur as a result of any activity other than tampering. This motion-sensing feature is, in fact, sufficiently sensitive to provide a small but easily recognized transient signal that occurs as the fuel transfer equipment contacts the top of the storage silo.

INTRODUCTION

The spent fuel bundles from Canadian deuterium-uranium (CANDU) reactors are initially stored in pools provided for that purpose within the reactor containment areas. As the storage areas become full, it is necessary to move the “cooled” fuel bundles into an alternative storage system. Storage of spent fuel in specially designed dry-storage silos is the presently accepted means for long-term disposition.

Prior to sending CANDU fuel bundles to dry storage, a large number of such bundles are placed into specially designed storage canisters that are then welded shut. Canisters are transferred to the silos in a heavily shielded transfer apparatus. The dry storage silos are designed so that each will hold nine of the sealed canisters (see Fig. 1). Typically the silos contain “verification tubes” that run along the length of the silo to enable the radiation profile within the silo to be periodically measured. Although the silos are considered to be very secure, every possible means by which material might be removed from the top, bottom, or side of the silo must be considered. Manual measurement of the radiation levels present in the verification tubes is presently the most reliable method for ensuring that the stored materials are still present.

Ideally, the radiation profile of each silo would be periodically inspected to verify the presence of each cask within each silo. As the number of silos continues to grow, however, the labor intensity of that task becomes overwhelming. A means for reliable, continuous monitoring of each silo could significantly reduce the labor intensity of the monitoring process without compromising the security of the stored materials. A simple sensor system, capable of being integrated into a facility-wide monitoring network has been developed and demonstrated by Oak Ridge National Laboratory (ORNL). The system uses inexpensive sensors to monitor the presence of the top and bottom canisters, verify the direction of any fuel transfers, and detect any attempt to tamper with the monitoring system.

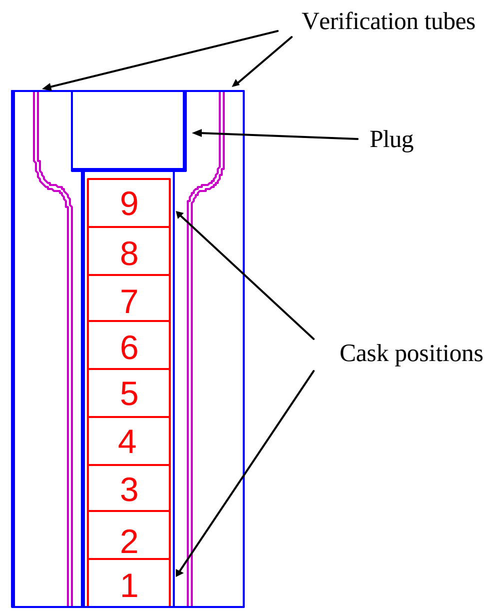

Fig. 1. Typical CANDU dry storage silo configuration.

SENSOR SYSTEM DESCRIPTION

Inexpensive argon-filled (1-atm) ionization chambers, with a chamber volume of about 25 mL are employed in the silo monitoring sensor system. The ion chambers were manufactured from simple components; copper tubing, wire, epoxy, a ceramic insulator, and some argon gas. Lithium coin cells are used as the bias voltage source for the chambers, which consume infinitesimal quantities of current. The signal from the ion chamber is amplified by a two-stage, single-supply, low-power, amplifier. Both the amplifier and ion chamber can be reliably powered for up to 10 years (battery shelf life) from compact lithium battery sources. The total material costs for a single sensor channel (dominated by the amplifier enclosure and the batteries) are much less than $100.

Although the bias voltage on the ion chamber is small (12 V) the radiation levels in the verification tubes are substantial (20 R/h or more). Consequently, the sensitivity of the low-voltage chamber is quite adequate for the monitoring task. Schematically, a single channel of the sensor system is shown in Fig. 2.

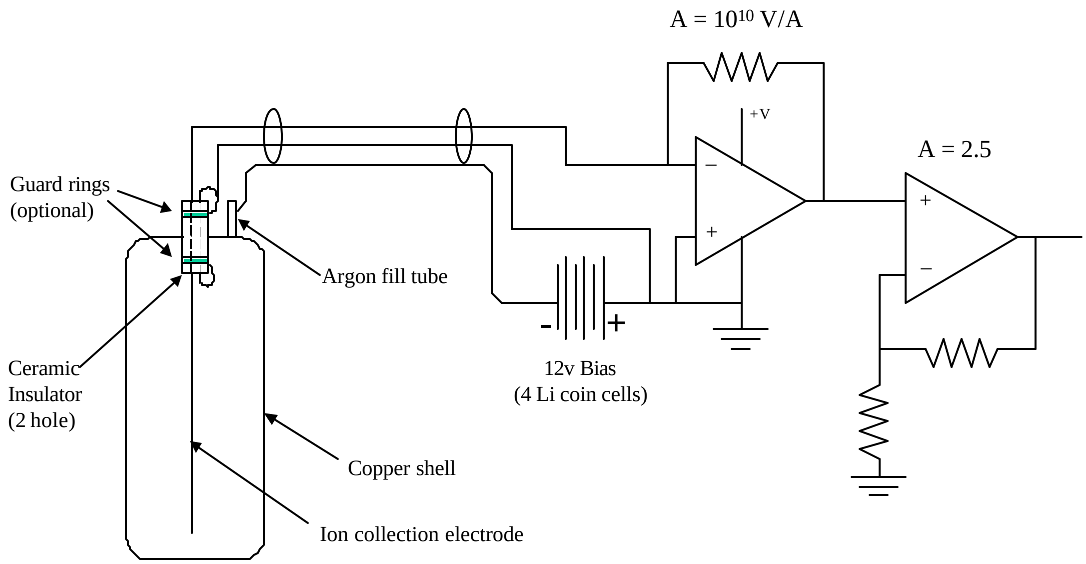

Fig. 2. Schematic representation of ionization chamber and amplifier.

The sensor is connected to the amplifier by a two-conductor shielded cable; the shield is used as the bias voltage conductor and is connected to the ion chamber shell via one of the argon fill tubes. One of the additional conductors is used as the ground connection, which connects to an internal and external guard ring around the center electrode. Due to the low bias voltage, the guard rings on the ion chamber are probably unnecessary but were included in the research prototypes. The third conductor carries the signal from the collection electrode of the ion chamber. A photo of a complete sensor channel is shown in Fig. 3. The compact amplifier housing slips easily into the verification tube. In this example, a shielded pair (with connector) was used to supply the amplifier power and extract the sensor signal through the sealing device that plugs the tube.

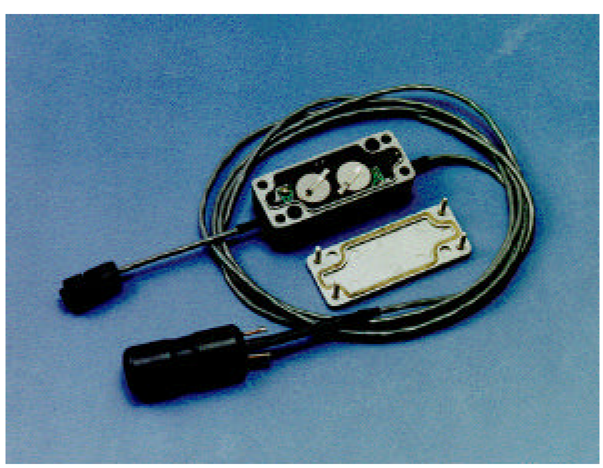

Fig. 3. Photo of ionization chamber and amplifier with amplifier housing open.

The capacitance between the shield and the signal conductor is employed as a distributed capacitance sensor that is highly sensitive to motion or vibration. When installed in the silo, the cable is at rest, and the amplifier output is very stable. However, any attempt to tamper with or remove the sensor will produce a signal excursion of hundreds of millivolts to several volts. A sensor deployed in the concrete silo only experiences motion from seismic sources, under normal circumstances. Due to their design, the sensors are highly sensitive to the slightest motion and capable of detecting any disturbance to their installed positions or the stability of the silo. This is demonstrated in the fuel transfer data, which show a signal of several hundred millivolts produced by the impact of the fuel transfer apparatus when it is lowered by a crane onto the top of the silo.

By strategically selecting the positions of the sensors within the verification tubes, three sensors are sufficient to monitor the direction of fuel transfer as well as the radiation level associated with the top and bottom canisters. The top sensor (I) is placed just past the bend in the verification tube and monitors the presence of the top canister in the silo stack. The next sensor (II) is located approximately one-half meter below sensor I. During the transfer of fuel into the silo, the radiation peak of the canister is detected first by sensor I, then by sensor II. Together, the signals from these two sensors provide positive verification that material is being transferred into rather than out of the silo. The third sensor (III), positioned near the bottom of the silo, monitors the presence of the lowest canister in the silo stack.

The combined signals from the three ion chambers enable the presence of the top and bottom canisters to be continuously monitored and the direction of any fuel transfer to be positively verified. The motion-sensing signals from the sensor cables prevent the undetected removal or alteration of the sensor systems and detect any shock to the silo, as would occur if the silo wall were being forcibly breached.

CALIBRATION AND TESTING

Calibration of the sensors was performed at the ORNL Radiation Standards and Calibration Laboratory (RaSCaL), using a cesium-137 source and calibrated attenuators. Several sensor systems were manufactured as research prototypes leading to the current design. The first unit of this particular configuration was manufactured and subjected to initial tests to verify the design concept. When the design was finalized, four more units were manufactured as a single batch, using a set of identically prepared components. The calibration data for the four sensors showed them to be very uniform in their responses with a maximum variation in radiation response of only 4% from unit to unit.

A small amount of environmental testing was done to simulate the deployment scenario for which the system was designed. In that scenario, the amplifier is located above the bend in the verification tube, and the ion chambers are located below the bend. Consequently the ion chambers are exposed to greater temperatures than the amplifier, while all of the components are subject to extreme humidity. The environmental test data showed no effects due to temperature or humidity that would affect the reliability of the sensors.

The amplifiers and ion chambers were placed in sealed containers, containing small volumes of water to maintain saturated humidity over a wide range of temperatures. The components remained in conditions of saturated and condensed humidity for 18 hours. The ion chambers were maintained at a temperature of about 47 °C for a period of about eight hours at the beginning of the tests and then allowed to cool to 22 °C for the remainder of the test to ensure condensed humidity was present. The preamplifiers were maintained at around 28 °C for the majority of the 18-hour test cycle but were heated as high as 43 °C briefly, to observe the temperature sensitivity.

During the limited environmental tests, there were virtually no effects due to humidity or temperature and after the tests, recalibration showed the sensitivity to be unchanged. Only two of the systems showed any measurable change in their output voltages during the environmental tests. At the elevated amplifier temperature, one showed an offset voltage change of 5 mV and another 3 mV. No response to the humidity conditions was observed at all. Immediately after the environmental exposure tests, the units were dried and returned to the RaSCaL facility for recalibration. There was essentially no change in the response. Representative results are shown for two of the units in Fig. 4.

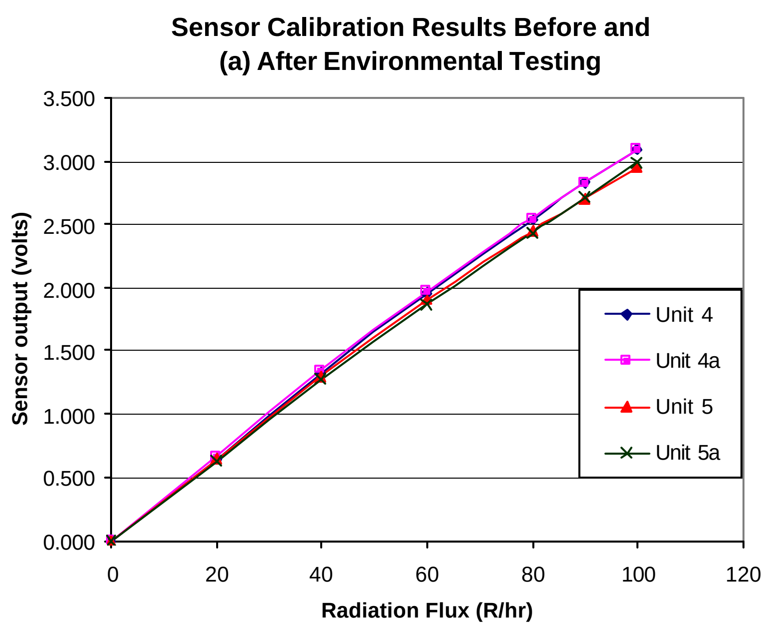

Fig. 4. Representative comparison of performance before and after environmental tests.

FIELD TEST DATA

The five research prototype sensor systems were taken to a CANDU dry storage silo field for testing. Initially, one of the sensors was lowered into a verification tube in a filled silo to observe the radiation profile and establish deployment depths for the sensors. The sensor was lowered using a carefully prepared device that simultaneously measured the cable length deployed into the verification tube and the radiation level. The sensitivity to the radiation levels from the first 8 canisters is dramatic and the sensitivity to canister 9 is quite adequate for verification. The data are shown in Fig. 5.

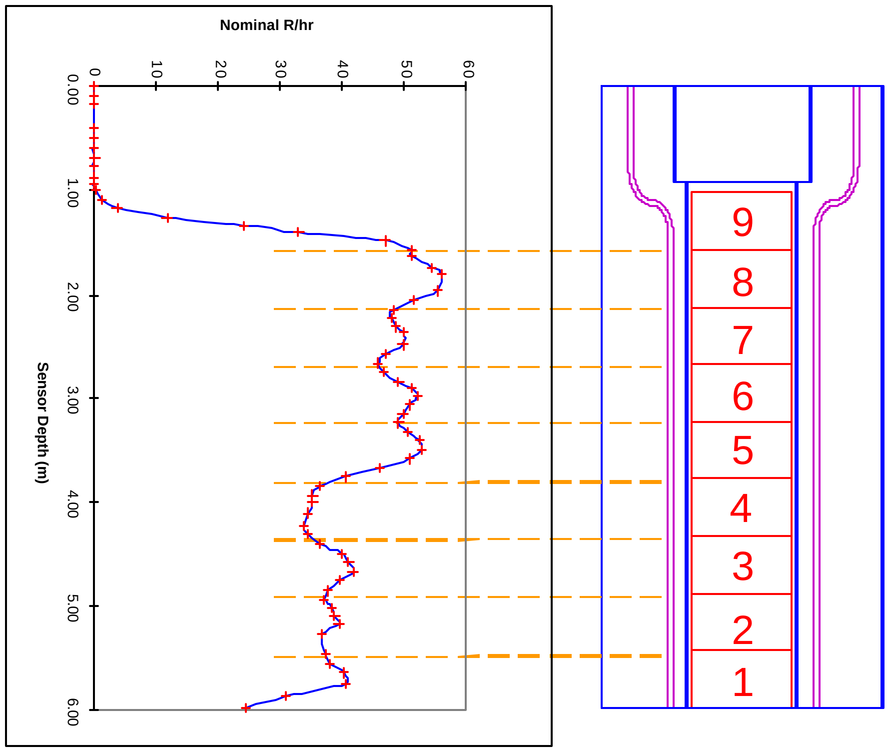

Fig. 5. Typical silo radiation flux profile as measured in verification tube.

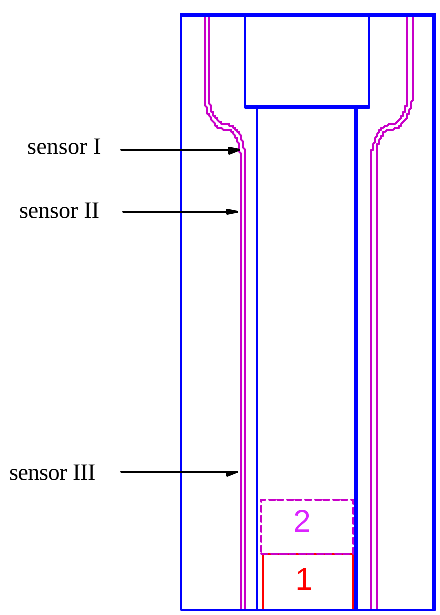

Fig. 6. Field test silo diagram showing sensor positions used during fuel transfer.

Figure 6 shows the positions into which the sensors were placed during the fuel transfer measurements. The silo that was chosen for the test already had one canister present and the second canister was being prepared for transfer. Sensor I was located just past the bend in the verification tube, and sensor II was located approximately one-half meter lower. Because the silo already contained one canister, sensor III was positioned so that it would be just above the second canister after it was deposited. In this way it was able to monitor the passage of the second canister as it was lowered into the silo. If the silo had been empty, sensor III would have been placed to reside just above the top of the lowest canister. In that position, it could monitor the passage of the canister and would be able to continuously monitor its radiation level without being subject to any shielding effects from the next canister. Of course, in that position, it would also see the combined radiation flux from the two canisters.

Figure 7 shows the sensor signals that were acquired during the transfer of canister two into the silo. The plot shows the voltage output of the three sensors as a function of time for approximately 3 minutes during the fuel transfer process. The first significant feature in the data is a voltage spike that occurs simultaneously on all three measurement channels. This represents the instant at which the transfer apparatus was lowered, by crane, onto the top of the silo and is due to the associated seismic impulse. Though the units of the plot are in R/h, it must be emphasized that this spike is not radiation-induced but represents a vibration-induced voltage peak of about 500 mV for sensor I, 350 mV for sensor II, and about 60 mV for sensor III.

Sensor III, (located well above the top of canister 1) initially indicates a radiation level of approximately 3 R/h, while the other two sensors register negligible radiation. As canister 2 is lowered into the silo, the passage of the canister is indicated by the smooth signal peaks in each of the three sensors. Though the sensors all had similar performance, sensor I indicates a maximum of approximately 42 R/h, while sensors II and III indicate peaks of approximately 50 R/h. The lower radiation level from sensor I is thought to be due to its location at the bottom of the bend in the verification tube. That bend is probably not as abrupt as is indicated in Fig. 6. As a result, there is probably additional shielding due to the concrete between the verification tube and the inner wall of the silo at that location. Finally, the radiation level measured by sensor III is increased to about 10 R/h after canister 2 is lowered into place.

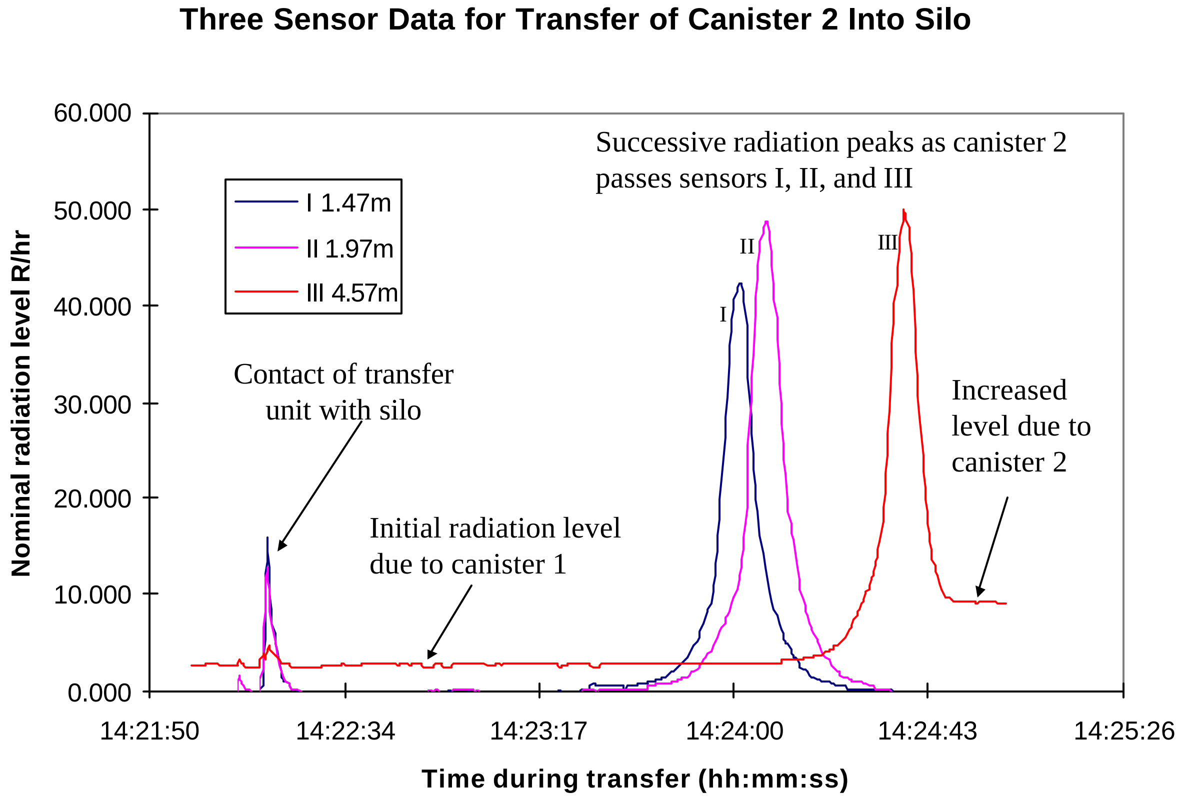

Fig. 7. Plot of sensor signal outputs during transfer of second canister into silo.

DISCUSSION OF RESULTS

As the number of dry storage silos continues to increase, the need for inexpensive and reliable monitoring systems will take on greater priority. The preliminary results to date indicate that the system that has been demonstrated can play an important role in monitoring CANDU dry storage silos. The sensor system is based on inexpensive components and is simple enough to be mass-produced in large quantities by a semi-skilled work force. The sensors appear to be robust enough to survive in the hot and humid environment of the verification tubes and need only have their batteries replaced every 10 years.

The sensor system appears to be very reliable, based on the tests performed to date. By monitoring the status of the radiation level at the top and bottom of the silo, undetected removal of material from the silo is virtually impossible. In addition, the direction of fuel canister movement can be verified during fuel transfer activities. The motion sensing feature of the sensors provides security against the undetected removal or modification of the sensor systems and is sufficiently sensitive to detect attempts to forcibly breach the silo walls.

ACKNOWLEDGEMENTS

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