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CURRENT STATUS OF INTEGRITY ASSESSMENT BY SIPPING SYSTEM OF SPENT FUEL BUNDLES IRRADIATED IN CANDU REACTOR

JONG-YOUL PARK[a,b], MOON-SOO SHIM[b] and JONG-HYEON LEE[b,c,d*]
[a]KEPCO Nuclear Fuel Co., Ltd., 1047, Daedeokdaero, Yuseong-gu, Daejeon 305-353, Republic of Korea
[b]Graduate School of Green Energy Technology
[c]Graduate School of Department of Advanced Materials Engineering
[d]Rapidly Solidified Materials Research Center, Chungnam National University, 79 Daehak-ro, Yuseong-gu, Daejeon 305-764, Republic of Korea
[*]Corresponding author. E-mail : jonglee@cnu.ac.kr

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In terms of safety and the efficient management of spent fuel storage, detecting failed fuel is one of the most important tasks in a CANada Deuterium Uranium (CANDU) reactor operation. It has been successfully demonstrated that in a CANDU reactor, on-power failed fuel detection and location systems, along with alarm area gamma monitors, can detect and locate defective and suspect fuel bundles before discharging them from the reactor to the spent fuel storage bay. In the reception bay, however, only visual inspection has been used to identify suspect bundles. Gaseous fission product and delayed neutron monitoring systems cannot precisely distinguish failed fuel elements from each fuel bundle. This study reports the use of a sipping system in a CANDU reactor for the integrity assessment of spent fuel bundles. The integrity assessment of spent fuel bundles using this sipping system has shown promise as a nondestructive test for detecting a defective fuel bundle in a CANDU reactor.

KEYWORDS : Sipping System, CANDU Reactor, Integrity Assessment, Defective Fuel bundle

1. INTRODUCTION

During the normal operation of a CANDU reactor, fission product gases accumulate in the fuel-to-sheath gap as the uranium dioxide fuel pellets experience nuclear fission. When a fuel sheath fails during normal reactor operations, coolant can enter the fuel-to-sheath gap, releasing fission products such as volatile species of noble gases or iodine into the primary heat transport system coolant.[1]. Nuclear fuel can be damaged under unexpected circumstances in a reactor. Fuel rods can fail as a result of debris fretting, delayed hydrogen cracking, and other factors. There are generally four causes of fuel defects, as outlined in Table 1.[2]

After many years of operation in CANDU reactors, the use of on-power failed fuel detection and location systems, along with alarm area gamma monitors, have successfully demonstrated that most, if not all, defective and suspect fuel bundles can be located before discharge to the reception bay. In general, only visual inspection has been used in the reception bay to identify suspect bundles. CANDU reactors in Korea have a delayed neutron detection system for locating failed bundles. Other methods are only available for identifying and locating failed fuel, including coolant sampling techniques and online gaseous fission product (GFP) monitoring of dissolved fission products in the primary coolant. There is no efficient method of confirming that a defective bundle has been discharged, other than observing a decrease in coolant activity levels. When a CANDU reactor has a defective fuel bundle during its operation, the defective fuel bundle should be discharged by releasing two fuel bundles at a time from the corresponding fuel channel until the failed fuel bundle is found. GFP and delayed neutron monitoring systems cannot precisely distinguish failed fuel elements from each fuel bundles. Discharged bundles are transferred from the storage pool to the modular air-cooled storage canister facilities that store the intact fuel bundles. An integrity assessment of spent fuel bundles irradiated in a CANDU reactor is needed to separate any suspect or defective bundles with fission products released in detectable quantities. Therefore, a sipping system was designed and built to enclose an irradiated bundle inside a sealed container at the bottom of the reception bay. The integrity of spent fuel bundles was assessed by this sipping system. This study investigated the integrity assessment of spent fuel bundles by using a sipping system in a CANDU reactor. The integrity assessment results have shown promise for this nondestructive sipping test.

Table 1. Causes of Defective CANDU Fuel Elements

Causes of Failure	Description of Mechanism
Debris Fretting	Debris, carried by the coolant, circulates around the primary heat transfer system (PHTS), which can cause fretting of the fuel sheath if this debris is lodged between adjacent elements.
Stress Corrosion Cracking (SCC)	Corrosive iodine fission products that are produced during the nuclear fission process in the fuel pellets can result in sheath cracking with pellet-sheath interaction during power ramping maneuvers.
Delayed Hydrogen Cracking	Hydrogen can diffuse to areas of high stress and low temperature, resulting in cracking near end-cap welds.
Manufacturing Flaws	The end caps of the fuel elements may have possible faulty welds or fabrication flaws (porous bar stock).

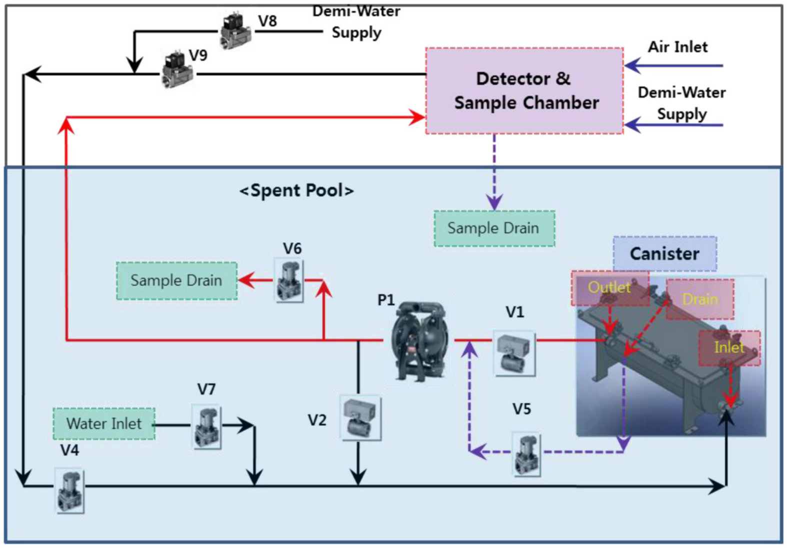


Fig. 1. Flow Schematic Diagram of the Sipping System

2. EXPERIMENTAL

2.1 Fluid Analysis of the Sipping System

Sipping is the most common technique used to locate fuel failures in both Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs). Identification of fuel rod failure is based on detecting the activity of fission products released through defects during sipping.[3] The measured radioisotopes include krypton, xenon, cesium, and iodine.[4] The widely known sipping technology used for inspecting defective fuel is largely divided into vacuum sipping, dry sipping, wet sipping, or in-mast sipping, depending on physical phenomena and the state of the fission products to be detected. However, in a CANDU reactor, only visual inspection in the reception bay has been used to identify suspect bundles. The Korea institute for nuclear safety (KINS) recommended the enforcement of continuous integrity assessments of the spent fuel bundles. This study adopted a sipping measurement technology to determine the radioactivity of gases and liquid samples holding fission products in a CANDU reactor. The sipping system employed two types of gamma detectors to increase the reliability of measurement and used the vacuum process for fission nuclides that may escape through defects or holes in the fuel element. The flow schematic diagram of the sipping system is shown in Fig. 1.

The sipping system consisted of a canister, valve, pump, stand, piping, and fittings. V means valve; for which air operated rotary ball valves were used. P means pump. The maximum flow rate of the pump was 133 liter per minute. The system was installed in the reception bay of a CANDU reactor to prevent the fuel inserted in the canister from leaking to the outside. For waterproofing, the canister was sealed with radioactivity-resistant polyurethane. The canister, coupled with the valve console, was installed on the bottom of the reception bay at a depth of 5 m. The control unit consisted of programmable logic controller (PLC) -based control equipment and a flowchart diagram display. The system panel, which was a box-shaped structure installed on an operation space outside the storage pool, included a local power panel electrically controlling pumps and valves, an air service unit supplying compressed air, and a valve controlling fluid flow. The NaI scintillation detector and other analysis circuits measured gamma rays from liquid samples. The range of energy to be measured was 50 keV–3.5 MeV.

The analysis of fluid mechanics was performed using the FLUENT software developed by ATES Company under the Boussinesq assumption, in the Laboratory of Mechanical Engineering department at Chungnam National University[5]. The inside fluid flow of the canister was treated as incompressible fluid.

2.2 Acceptance Test of the Sipping System

An acceptance test was used to test the energy resolution, sensitivity, and counting precision of a counting device of the sipping system. The test was performed in the Korea Research Institute of Standards and Science(KRISS) in accordance with the National Metrology Institute of Korea’s bylaws based on the Framework Act for National Standards. The test was conducted as per the quality control of nuclear medicine instruments proposed by the nternational Atomic Energy Agency(IAEA) [6]. The sipping system was lined up in parallel to the standard system of KRISS, as shown in Fig. 2. The calibration source used ^{137}Cs with 1μCi ($6.132X10^4$Bq (Dec. 12. 1979). The geometry factor was 0.5. The power of 800 volts direct current(VDC) was supplied. The same disk source supplied the developed system and the standard system.

2.3 Performance Test of the Sipping System

The performance test assessed the feasibility of inspecting the fuel integrity in a CANDU reactor by using the sipping system. The sipping system was installed in the reception bay of Wolsung Unit 4. Five intact spent fuel bundles among the discharged fuel bundles were selected for the feasibility test.

2.4 Application of the Sipping System

The sipping system was used to assess the integrity of spent fuel bundles in a CANDU reactor. Four spent fuel bundles were selected as suspected fuel bundles in Wolsung Unit 4 and the integrity assessment was performed by using the sipping test. The surfaces of the outer fuel elements were visually tested. In addition, the integrity of spent fuel bundles was assessed in Wolsung Unit 2. The four suspect fuel bundles were inspected to locate the failed fuel bundle. The sipping system and the visual inspection system were applied to inspect fuel integrity.

3. RESULTS AND DISCUSSION

3.1 Fluid Analysis of the Sipping System

The fluid mechanics in the canister of the sipping system were analyzed by using computational fluid dynamics. The velocity vector in the canister of the sipping sys-

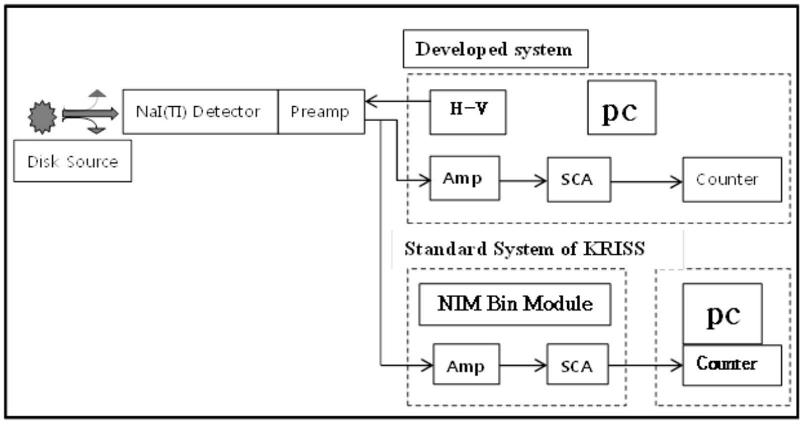


Fig. 2. Diagram of the Performance Test for the Sipping System

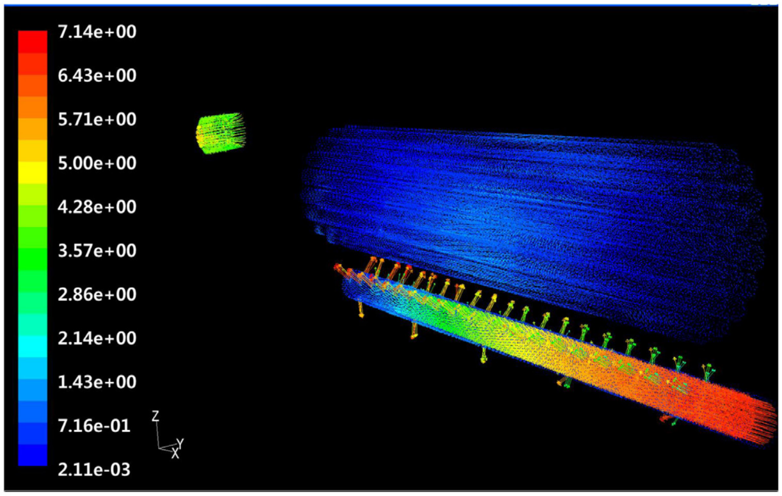


Fig. 3. Velocity Vector in the Canister

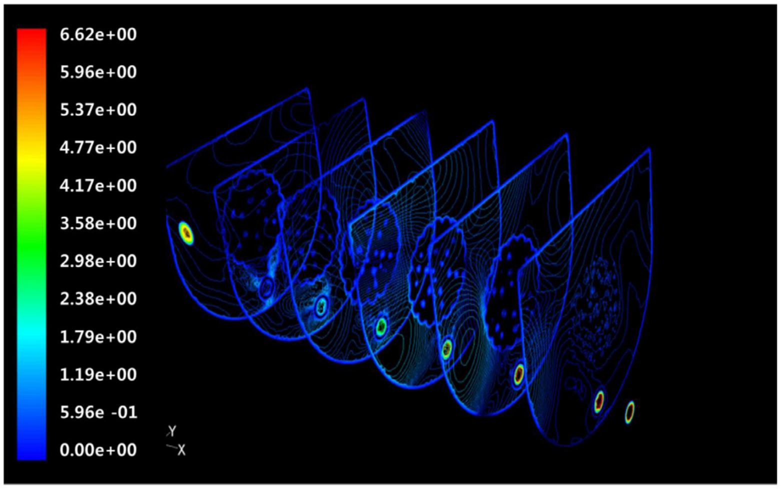


Fig. 4. Velocity Distribution in the Canister

tem is shown in Fig. 3. The velocity at the entrance of the canister was 3.75 m/s and that at the outlet was 6.40 m/s. The velocity distribution in the canister of the sipping system is shown in Fig. 4. The velocity in the entrance of the canister was almost twice as fast as in the outlet of the canister. However the ejection velocity of the orifice in the entrance of the canister was lower than that of the orifice in the outlet of the canister. In the inner flow of the sipping system, the canister provided a smooth flow of coolant through the fuel bundles. It was found that the sipping system easily and efficiently located the failed fuel bundle. It was found that the sipping system could monitor the fission product by circulation of the coolant inside of the failed fuel bundles.

3.2 Acceptance Test of the Sipping System

Energy resolution is the ability of the detector to accurately determine the energy of the incoming radiation; this is a very important parameter in determining the overall acceptance of a sipping system. An important measurement to assess the efficiency of the scintillation counting device is full width at half maximum (FWHM). The formula for determining the energy level percentage of a particular radionuclide is

$$R(Er) = FWHM \times 100/Er \qquad (1)$$

Table 2. Sensitivity Test Conditions

Item	Contents
Radioactivity Source	^{137}Cs
Radioactivity	1 μCi (6.132 × 10^4 Bq (Dec. 12, 1979), point source
Energy Window	Main photon peak (KeV) ± 10%
Distance of Detection	Attachment of source on the surface of the detector
Counting Time	1,000 s

Table 3. Test Conditions for Counting Precision

Item	Contents
Radioactivity Source	^{137}Cs
Radioactivity	1 μCi (6.132 × 10^4 Bq (Dec. 12, 1979), point source
Energy Window	Main photon peak (KeV) ± 10%
Distance of Detection	Attachment of source on the surface of the detector
Counting Time	1,000 s
Repetition of Detection	5 times

where R(Er): energy resolution (%), Er: mono-photon energy (keV).

Energy resolution is expressed as a percentage of the FWHM of a specific energy. In the energy resolution test of the sipping system, the energy resolution was 6.51%. The energy resolution of the KRISS standard was 6.57%. The difference between the sipping system and the standard was less than 7%. The comparison between the sipping system and the KRISS standard showed a margin of error for the sipping system of approximately 0.91%. Because this error margin of 0.91% is less than 1%, the performance of the sipping system in the energy resolution was equal to that of the standard of KRISS.

Sensitivity testing was performed by measurements on a certified ^{137}Cs gamma-radiation source under the test conditions shown in Table 2. The formula for determining the sensitivity is

$$E(Ab) = CPS \times 100/DPS \tag{2}$$

where E(Ab): counting efficiency (%), CPS: count per second, DPS: disintegration per second.
Table 2 shows the conditions of the sensitivity test.

In the sensitivity test of the sipping system, the sensitivity was 12.19%. The sensitivity of the KRISS standard was 12.13%. The difference between the sipping system and the standard was less than 0.06%. The comparison between the sipping system and the KRISS standard showed a margin of error for the sipping system of approximately 0.49%. Because this error margin of 0.49% is less than 1%, the sensitivity of the sipping system was almost the same as the sensitivity of the standard.

The counting precision test calculates the value of x^2 under the test conditions shown in Table 3 from the following relationship:

$$x^2 = \frac{\sum\{C_1 - C\,(m)\}^2}{C(m)} \times 100 \tag{3}$$

Table 4. Detection Count for Accuracy in Sipping System

Counting Rate (C_1)	Avg. Counting Rate (C(m))	C_1 – C(m)	(C_1 – C(m))^2	∑(C_1 – C(m))^2
3,841 cps	3,838 cps	3	9	315
3,842 cps		4	16	
3,846 cps		8	64	
3,823 cps		-15	225	
3,839 cps		1	1	

where x^2: counting precision, C_1: an individual count, C(m): mean of the 10 counts.

The results of the counting precision test of the sipping system are shown in Table 4. The results of counting precision for the KRISS standard are shown in Table 5.

In the calculation results of Equation (3), the counting precision of the sipping system was 8.2 and that of the KRISS standard was 5.9. These calculations meet the international quality control requirement of a value less than 16.92.[5] The difference between the sipping system and the standard was 0.88%. Therefore, the detection performance of the sipping system was verified.

3.3 Performance Test of the Sipping System

Three basic gamma activities were measured: background, liquid gross, and gas gross. The radioactivity of fuel bundles according to the sipping test showed almost twice as much background level. This radioactivity was confirmed as the radioactivity of intact spent fuel bundles. The functional test of the sipping system was performed as shown in Table 6.

This performance test in a CANDU reactor successfully proved that the sipping technology was effectively used to assess the integrity of spent fuel bundles irradiated in the reception bay. The threshold value for the discrimination of fuel failure was also confirmed from the radioactivity data measured by the sipping system.

3.4 Application of the Sipping System

In Wolsung Unit 4, no defective fuel element was found, although there was a small scratch on the surface of the fuel element, as shown in Fig. 5. The sipping system employed two types of gamma detectors to increase the reliability of measurement and used the vacuum process for fission nuclides that may escape through defects or holes in the fuel element. Two gamma detectors were

Table 5. Detection Count for Accuracy in Standard

Counting Rate (C_1)	Avg. Counting Rate (C(m))	$C_1 - C(m)$	$(C_1 - C(m))^2$	$\sum(C_1 - C(m))^2$
3,805 cps	3,804 cps	1	1	226
3,810 cps		6	36	
3,812 cps		8	64	
3,793 cps		-11	121	
3,802 cps		-2	4	

Table 6. Functional Test Results of the Sipping System

Contents	Test results
Canister Sealing, Pump and Valve	- Canister sealing: Ethylene Propylene Diene Monomer (EPDM)for radiation resistance - Pump performance: 2HP, 133 L/min - Valve operation in water: good
System Condition and Operating Program	- Pressure meter: Max 10 kg/㎠ - Flowmeter: turbine type, max. 38 L/min - Operating manual/auto program: good
Detector Performance	- Min. detectability: 0.01 Bq/cc - Shielding thickness of detector: Lead, 5.08cm - Operating MCA program: good
Material Suitability	- Main material: stainless steel - Flexible hose: polyurethane

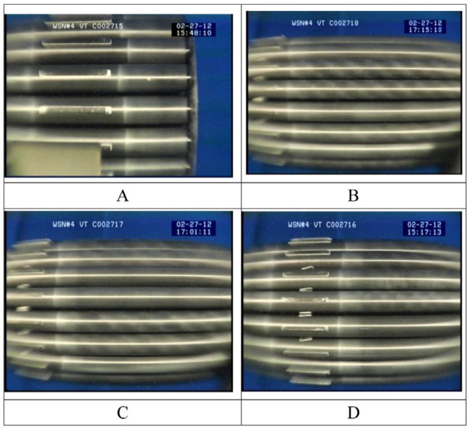


Fig. 5. Visual Inspection of Fuel Bundles in Wolsung Unit

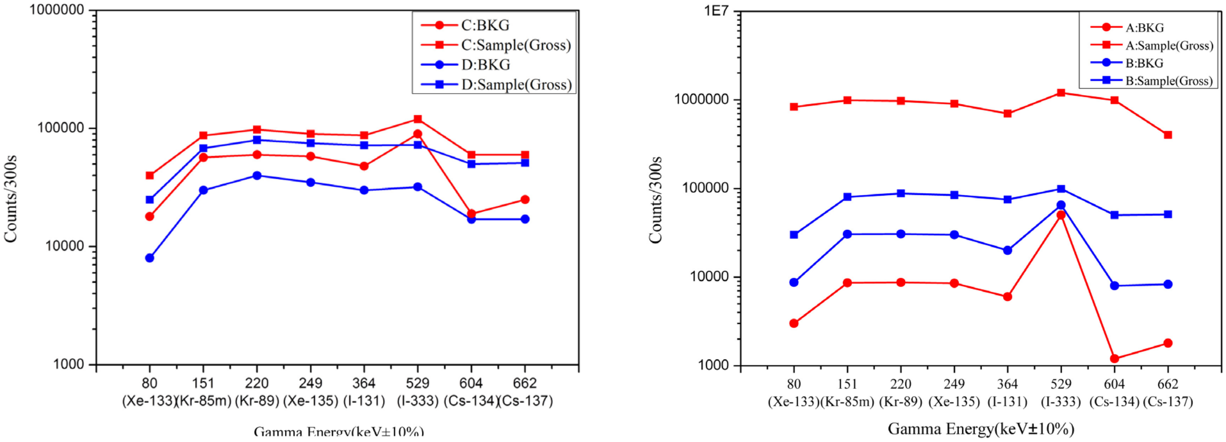


Fig. 6. Sipping test results in Wolsung Unit 4

installed in the sipping system alternately. The results of the sipping test are shown in Fig. 6. Fuel bundle “A” in Fig. 6 was one hundred times more radioactive than the background(BKG) level in the fission nuclides of Xe and Kr. The Xe-133 nuclide was also detected by the gamma detector, as shown in Fig. 7. Any indication outside the bundle A was not found. Fuel bundles “B,” “C,” and “D” were just two or three times more radioactive than the BKG level, which was the radioactivity level corresponding to intact fuel. In addition, no fission nuclide was found in any other fuel bundles, except activated corrosion products like Ni-57, Cu-61, and Co-56.

In Wolsung Unit 2, the four suspect fuel bundles were inspected to locate the failed fuel bundle. This visual inspection determined that “H” fuel had a defect on the end plug of the fuel element, as shown in Fig. 8. Sipping testing was performed for the fuel bundles just after visual testing. The radioactivity levels of fuel bundles examined for 300 s are shown in Fig. 9. Failed fuel bundle “H” was examined for 100 s by a gamma detector because it emitted unnecessarily high radioactivity. The radioactivity levels of “E,” “F,” and “G” fuel bundles were within two times the background value equivalent to the radioactivity of the intact fuel bundle. In case of fuel bundle “H,” the radioactivity level was over 30 times that of the BKG level in fission nuclides of Xe and Kr. No fission nuclides were found in fuel bundles “E,” “F,” or “G.”

The radioactivity of “A” fuel bundle in Wolsung Unit 4 and that of "H" fuel bundle in Wolsung Unit 2 showed too high a level of radioactivity. Therefore these fuel bundles were classed as the failed fuel bundles. The Gaseous Fission Product and delayed neutron monitoring systems along with alarm area gamma monitors in a CANDU reactor could monitor the coolant activity of the suspect fuel bundles. Then the failed fuel bundle was detected by the sipping system in the spent fuel storage bay. The validation of this method could be done by the poolside examination after disassembling the fuel bundle.

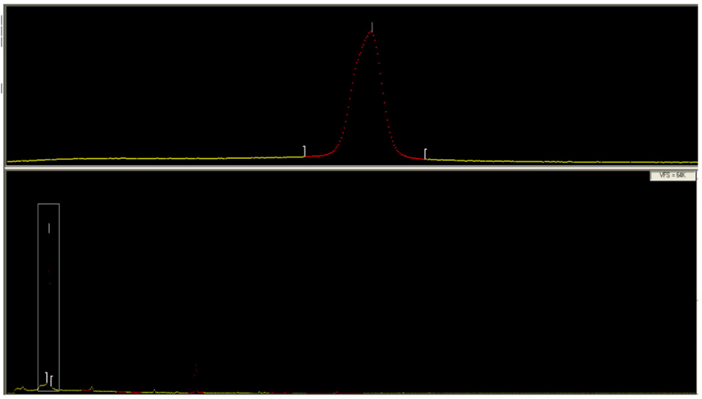
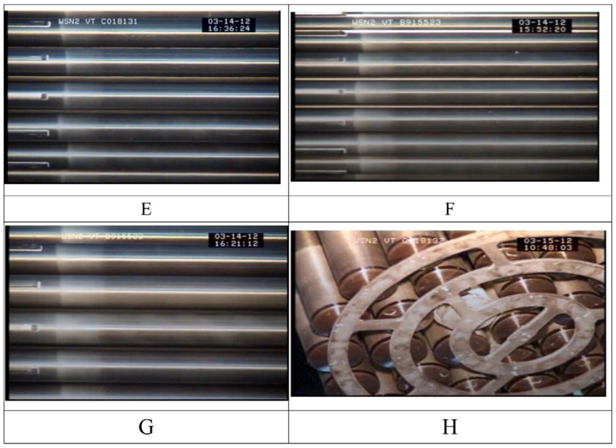


Fig. 7. Xe-133 Fission Nuclide Spectrum of Fuel Bundle "A"



E F G H

Fig. 8. Visual Inspection of Fuel Bundles in Wolsung Unit 2

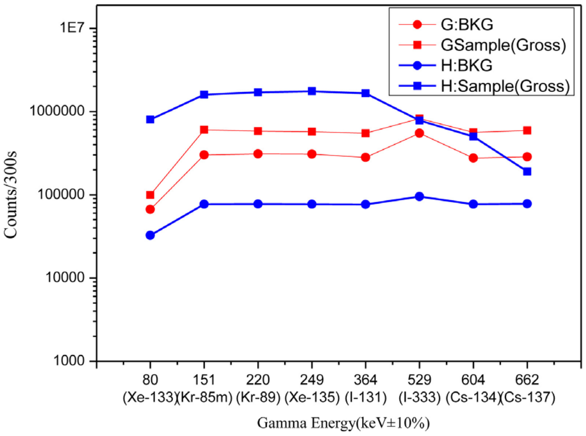


Fig. 9. Sipping Inspection Results in Wolsung Unit 2

4. CONCLUSIONS

A sipping system was developed to assess the integrity of spent fuel bundles irradiated in a CANDU reactor. The analysis of fluid mechanics in the sipping system using computational fluid dynamics showed a smooth flow of coolant through the fuel bundles. The acceptance test results of the sipping system performed in KRISS showed that the energy resolution, sensitivity, and counting precision of the counting device were almost the same as detailed in the KRISS standard. The performance test in a CANDU reactor confirmed the threshold value for the discrimination of fuel failure from the radioactivity data measured by the sipping system. The integrity assessment of spent fuel bundles was successfully performed by the sipping system, and has shown promise as a non-destructive test for detecting defective fuel bundles in a CANDU reactor.

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