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Development and characterization of a fiber-optic monitoring system for the key environment variables of the spent nuclear fuel pool at a nuclear power plant

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ABSTRACT

This study develops and characterizes a fiber-optic monitoring system for the key environment variables of the spent nuclear fuel pool (SNFP) at a nuclear power plant. The three key environmental variables indicating the SNFP status directly are its water temperature, water level, and radiation level. First, this study develops and characterizes the individual fiber-optic sensors for measuring the three key environmental variables and then assembles them into an integrated monitoring system. The individual fiber-optic sensors commonly use optical fibers to transmit the signals delivered from their sensing probes despite their different characteristics. For the fiber-optic temperature sensor (FOTS), two types of FOTS are developed: contact and non-contact types, which are distinguished by whether their sensing probes are in direct contact with water. The contact-type FOTS uses a copper metal cap as its sensing probe, and the non-contact-type FOTS uses an infrared optical fiber, whose peripheral surface is coated with an anti-fog solution as its sensing probe. The fiber-optic water level sensor (FOWS) consists of optical fibers with their ends connected to the sensing probes fabricated with a NaCl solution and stainless steel. The FOWS measures the water level using the Fresnel reflection phenomenon, i.e., reflection of a portion of incident light at a discrete interface between two media having different refractive indices. The FOWS identifies the water level by measuring the amount of light reflected at the interface between the sensing probe and its outside medium, which varies according to whether the sensing probe is in contact with water. The fiber-optic radiation sensor (FORS) measures the gamma radiation in the SNFP. The sensing probe of FORS is a cylindrical-shaped LYSO:Ce scintillator, whose peripheral is wrapped with aluminum foil as the reflector. After characterizing the three individual sensors developed in this study, they are assembled and tested at a model water pool, 500 mm × 500 mm × 500 mm in size. The performance test results shows that individual sensors can measure the changes in each environmental variable in real-time.

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1. Introduction

In March 2011, Fukushima Daiichi units 1–6 were struck by a large tsunami with a height of more than 14 m following a powerful 9.0-magnitude earthquake. The tsunami caused the complete loss of alternating current (AC) power. Owing to the prolonged loss of AC power, the spent nuclear fuel pool (SNFP) of Fukushima Daiichi Units 1–4 had not been cooled, and were impaired as a result. Because the key environmental variables indicating the SNFP status are generally monitored by the active devices operated by AC power, any loss of AC power leads to the status of a lack of information on the SNFP, which may cause confusion regarding accident management. The case of Fukushima Daiichi unit 4 SNFP highlights the importance of continuous monitoring of the key environmental variables in the SNFP under accident conditions. The task force established by the U.S. Nuclear Regulatory Commission (NRC) made several recommendations to improve the SNFP's safety, one of which was for NRC staff to order licensees to provide sufficient instrumentation to monitor the key environment variables at a SNFP (U.S. Nuclear Regulatory Commission, 2011; Wang et al., 2012).

The lessons of the Fukushima Daiichi Unit 4 SNFP accident require the development of an auxiliary monitoring system with

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the capability to monitor the key environmental variables, even when the main monitoring system failure due to a loss of AC power lasts for a long time, at least several days. The key environmental variables of the SNFP are water temperature, water level, and radiation level as recommended by the NRC. The three key environmental variables would change if a loss of AC power accident at the SNFP occurs and lasts for a long time. Monitoring of the three key environmental variables informs the operators if an abnormal situation or emergency occurs at the SNFP. As long as the SNFP is under the normal condition, the three key environmental variables are within their normal ranges specified by the technical specifications for a nuclear power plant (NPP). Otherwise, at least one of the three key environmental variables would deviate from its normal range. When the cooling capability of the SNFP is partially or totally lost for a long time, the SNFP water temperature would increase gradually and reach the water boiling point unless appropriate measures are taken at the right time. The SNFP water would then boil, which will cause a gradual decrease in the SNFP water level. If the top of spent nuclear fuel is exposed to air due to the reduced water level, the areal radiation level at the SNFP would increase rapidly because a decrease in the SNFP water level means a decrease in the radiation shielding material thickness.

Considering that the three key environmental variables would change almost sequentially as the accident situation worsens, this study proposes a methodology to assume the SNFP status consisting of the three steps that are represented by the key environmental variables to be monitored in priority during each step. The details of each step are as follows:

- *Step 1. SNFP water temperature monitoring*. This step measures the SNFP water temperature and checks if it is within the normal temperature range specified by the technical specification for an NPP. For example, the SNFP water temperature at Korean Kori Unit 1 and 2 during normal operation and refueling outage shall be within the range of 48.9–60 °C (Korea Hydro & Nuclear Power Co., 1989). If the SNFP water temperature deviates from the normal temperature range, a warning signal indicating that an abnormal situation begins shall be generated and passed on to the operators. If the SNFP water temperature exceeds the water boiling point, the key environmental variable to be monitored in priority would be shifted to the SNFP water level. This step is for the early phase of an accident.
- *Step 2. SNFP water level monitoring*. This step is to measure the SNFP water level and check if and how fast it is decreasing. During this step, the areal radiation level at the SNFP increases gradually as the SNFP water level decreases because water is both a coolant and radiation shielding material. The water level is more important from the viewpoint of accident management, so this step focuses on the SNFP water level. Two warning signals could be generated. The first is generated once a decrease in the SNFP water level has been recognized. The second is generated once the decrease rate of the SNFP water level has exceeded the prescribed value. This step is for the intermediate phase of an accident.
- *Step 3. SNFP radiation level monitoring*. This step is to measure the SNFP radiation level, in particular, to detect an abrupt increase in the radiation level. Once the top of spent nuclear fuel is exposed to air, the SNFP radiation level will increase abruptly, which is considerably higher than that in step 2. Although it is unlikely that this step would be triggered because significant time will pass before the detection of a large radiation dose rate, e.g., 1×10^3 mSv/h, the warning signal of a large radiation level could be generated. Once generated, however, the exposure of spent nuclear fuel to the air is imminent or has been already done, which shall be followed immediately by emergency measures, such as injecting borated water into the SNFP.

To implement the proposed methodology in an emergency situation, such as a loss of AC power accident, an auxiliary monitoring system shall be equipped at the SNFP. To this end, the auxiliary monitoring systems shall have at least the two following minimum qualifications:

- *Qualification 1:* to ensure that the three SNFP key environmental variables are monitored simultaneously and continuously from the main control room or at a safe location that is far from the SNFP but operators can have easy access to; and
- *Qualification 2:* to ensure that the monitoring system shall be operable even under a loss of AC power condition.

To meet qualification 1, fiber-optic sensors might be considered, which make simultaneous and remote measurements of physical variables even under harsh environments. To meet qualification 2, the use of a low-voltage direct current (DC) battery as a power source to the auxiliary monitoring system might be considered. Therefore, this study develops a monitoring system for the simultaneous and remote measurements of the three key environmental variables of a SNFP, which can be operated by an AC or a DC power source. The system consists of the three sensors: water temperature sensor, water level sensor, and radiation sensor.

2. Materials and methods

2.1. SNFP water temperature sensor

This study develops two types of fiber-optic temperature sensors (FOTS): contact and non-contact type, which are distinguished by whether their sensing probes are in direct contact with water. The FOTS measures the water temperature by detecting the infrared light emitted from the water at a certain temperature.

The temperature range to be measured by the FOTSs is from 30 to 70 °C, which includes the SNFP normal water temperature range from 48.9 to 60 °C specified by the Korean NPP technical specification. Wien's displacement law states that the peak wavelengths of thermal radiation, corresponding to the temperatures from 30 to 70 °C, are from 9.56 to 8.44 μm. Wien's displacement law is defined as

$$T \cdot \lambda_{max} = a \quad (1)$$

where T is the absolute temperature in kelvins (K), λ_{max} is the peak wavelength in μm, and '*a*' is a constant of proportionality as Wien's displacement constant, it equals 2897.8 μm·K.

This study uses an infrared optical fiber, PIR AgCl:AgBr polycrystalline fiber (PIR 900/1000, JT Ingram), to transmit the infrared light over the temperature range from 30 to 70 °C. The infrared fiber has many advantages; non-toxic, wide transmission range in 4–18 μm, and low signal attenuation in the middle infrared region (JT Ingram Technologies Inc., 2016). Table 1 lists the properties of an infrared optical fiber.

The sensing probe of the contact-type FOTS is a copper metal cap of which the inner and outer diameters are 3.5 mm and 5 mm, respectively. The material and size of the sensing probe is chosen from the previous studies (Kim et al., 2015; Frank and David, 2011; Jeong, 2012). The sensing probe of the non-contact type FOTS is an infrared optical fiber itself coated with an anti-fog solution. The main component of this anti-fog solution is a non-ionic surfactant. A change in water temperature may generate vapor on the surface of the infrared optical fiber, which reduces the detection efficiency of the FOTS (Wagner, 2001). To prevent the occurrence of this fogging phenomenon, the infrared optical fiber is coated with a spraying anti-fog solution onto its surface and drying several times (Kim et al., 2015; Kim, 2004).

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