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Harsh stress level design for accelerated life test of HLW repository monitoring sensor

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ABSTRACT

The high-Level Nuclear Waste (HLW) Repository has complex stresses such as high temperature, humidity, and radiation. And these stresses cause deterioration and cracks in the structure over time. And also, the leakage of radioactive waste from HLW can cause severe harm to humans. So structural health monitoring with monitoring sensors is crucial for safety. Once sensors are installed in the repository, it is impossible to uninstall them because of backfill and buffer. Therefore, a sensor that can work under the repository's environmental conditions for as long as necessary is needed. So, before installation, it is first required to assess the sensor life. An Accelerated Life Test (ALT) is typically used to assess durability and obtain life model within a short test time. Failure is induced under harsh conditions, and a life model is obtained using the failure data. When doing a reliability test such as ALT, it is necessary to produce the same failure mode. So, it is important to determine the appropriate harsh stress levels. If the stress levels are too high, the failure mode of a target could change. Conversely, if the stress levels are low, the test time gets long. Therefore, in this paper, an overview of the accelerated life test is provided, and experiments were conducted to determine appropriate harsh stress levels.

1. INTRODUCTION

With the increased interest and utilization of nuclear-generated energy, nuclear waste is increasing. High-level nuclear waste (HLW) has a high radioactivity level among nuclear wastes generated from nuclear power plants and has severe effects on humans.

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In addition, a considerable quantity of waste nuclides in nuclear waste has a very long half-life. Therefore, there is a need for a long-term storage facility (Kim et al., 2011). And it must be prevented that high-temperature heat from radioactive elements would affect the environment. High temperature and radiation exposure affect concrete strength (Ma et al., 2015, Field et al., 2015). In other words, heat and radiation are critical environmental factor due to HLW, and the Deep Geological Disposal System is one way to manage HLW from these environmental factors. HLW repository is a kind of Deep Disposal System with a depth of 500 to1000 meters and is separated into an Engineered Barrier System (EBS) and a Natural Barrier System (NBS). NBS refers to rock mass and geological environments that exist in a natural state around High-Level Nuclear Waste Disposal, and EBS is comprised of a disposal canister, buffer, and backfill disposal tunnel (Choi et al., 2008). A vertical deposition borehole is excavated at the bottom of the disposal tunnel. After that, the spent nuclear fuel is sealed in the disposal canister, the disposal canister is placed in the vertical deposition borehole, the empty space between the disposal canister and the rock mass is filled with a buffer, bentonite, and the disposal tunnel is filled with backfill to close it completely. (Kim et al., 2021) (Fig. 1).

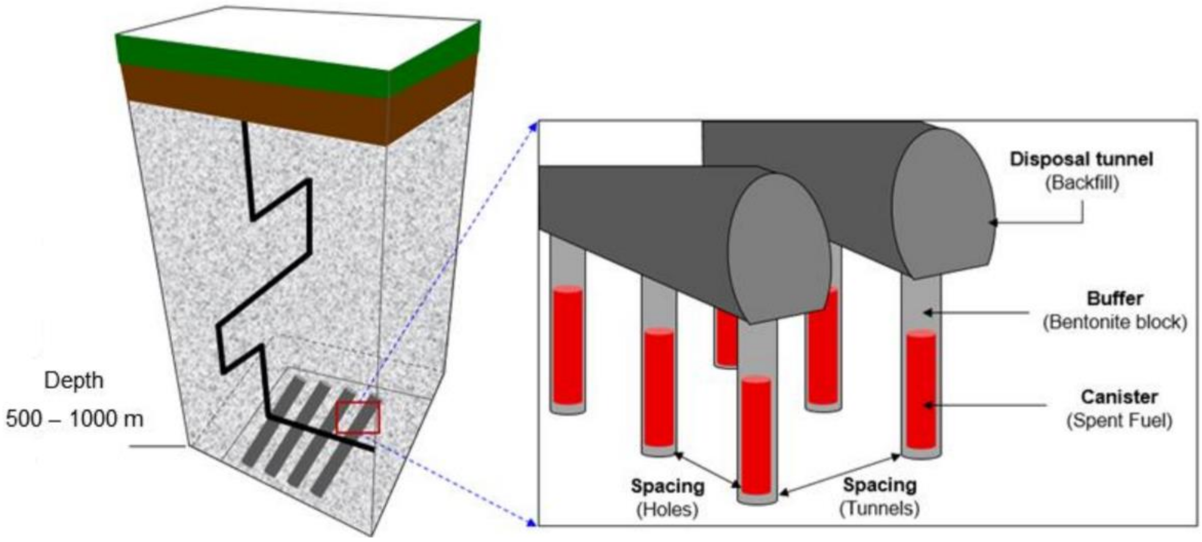

Fig. 1 Concept of EBS of HLW repository (Yoon et al., 2020)

Structural health monitoring with a monitoring sensor is necessary to verify that the repository effectively keeps hazardous waste out. The environmental conditions of these locations gradually increase the heat and radiation level from the original condition immediately after sealing the HLW and converge to a constant level after about 6-12 months and become a stable state for a very long time. In the disposal tunnel, the temperature is approximately 50°C, and there is nearly no radiation. And the canister has a temperature of approximately 95°C and a radiation level of about 0.1 Gy/hr. The typical monitored temperature range for an HLW repository is between 20°C and 90°C, and the typical monitored radiation range is between 0.1Gy/hr and 1Gy/hr (Delepine-Lesoille, Sylvie, et al., 2017). The monitoring sensors are installed in a disposal tunnel and a disposal canister (Fig. 2).

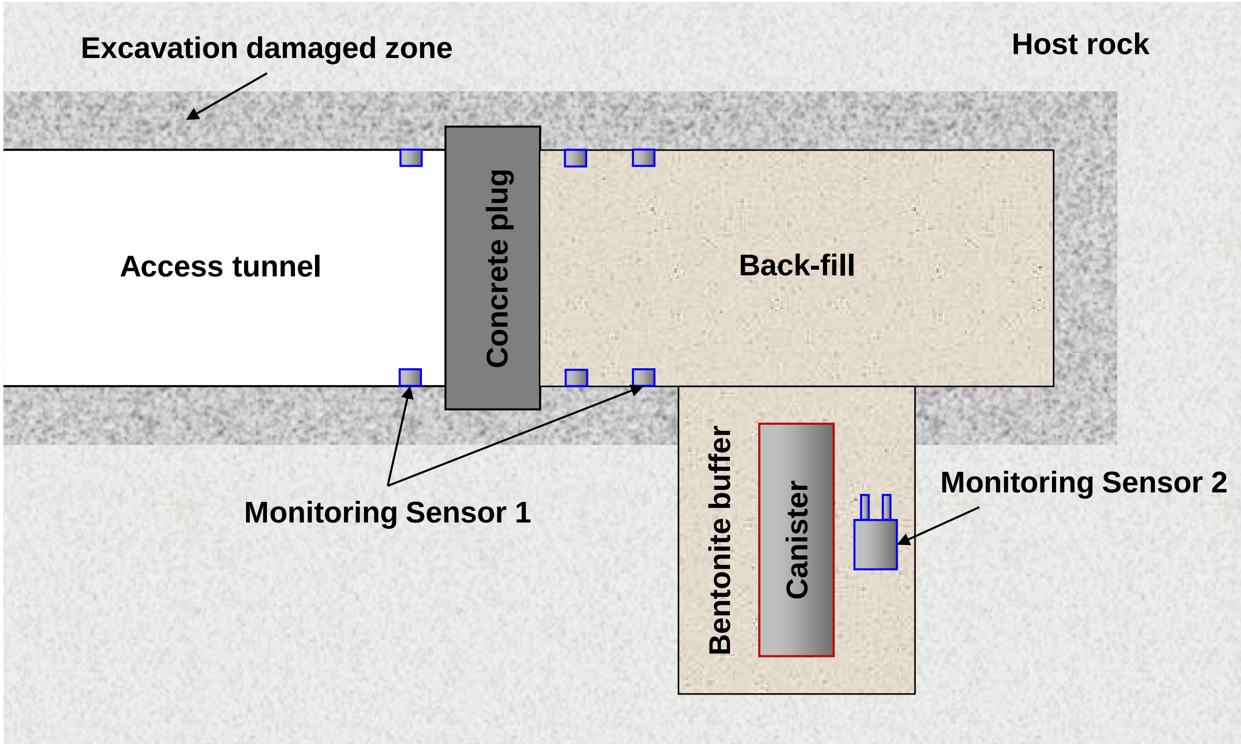

Fig. 2 Locations of the sensors at HLW repository

Once sensors are installed in the repository, it is impossible to uninstall them because of backfill and buffer. Therefore, a sensor that can work under the repository's environmental conditions for as long as necessary is needed. So, before installation, it is first required to assess the sensor life. For this purpose, the accelerated life test, which can produce a life model with a short test time under harsh stress conditions, is mostly utilized. When doing a reliability test such as ALT, it is necessary to produce the same failure mode. And to shorten test time, it is essential to design harsh stress levels appropriately. Therefore, in this paper, an overview of the accelerated life test is provided, and experiments were conducted to design appropriate harsh stress levels.

2. EXPERIMENTS

2-1. Experiment overview

This experiment is intended to design the harsh stress levels used in ALT. An accelerated life test is a method for predicting life under specific conditions by presenting a life model based on life under harsh stress conditions. It has the advantage of being able to obtain a life model in a short amount of time. When conducting this experiment, it is crucial to design harsh stress levels properly. If the stress levels are too high, the failure mode of a target could change. Conversely, if the stress levels are low, the test time gets long. In this experiment, PCB 603C01, a piezoelectric accelerometer widely used in industry, was used. The sensor is industrial shear mode accelerometer (Fig. 3). The following table. 1 displays the failure mode of the piezo sensor as determined by Failure Mode and Effects Analysis (FMEA).

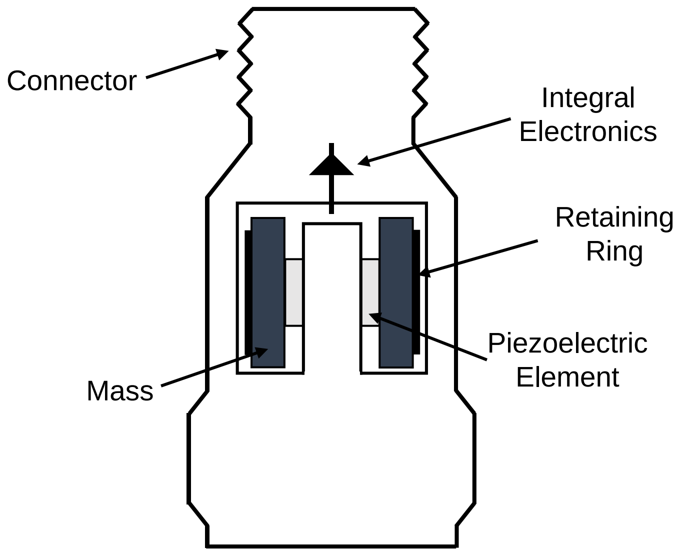

Fig. 3 Typical Industrial Shear Mode Accelerometer

Table. 1 FMEA of a piezo sensor (Data from Lim et al., 2015)

	Function	Failure Mechanism	OCC	Failure Effects	SEV	Failure causes	DET	RPN	Detection method
Outer tube	Signal generation	Breakage	4	Poor internal protection Poor signal	4	mechanical stress Temperature humidity	4	48	Voltage measurement
Piezo film		Destruction	2	Poor signal	5	Temperature humidity	2	40	
		Transformation	4				2	40	
Inner electrode		Breakage	3		3		2	18	

OCC: Occurrence probability of a failure mode represented as a value between 1 to 10
SEV: Severity of a failure represented as a value between 1 to 10
DET: Detection probability of a failure mode represented as a value between 1 to 10
RPN: OCC × SEV × DET, Risk Priority Number

2-2. Experiment setup

According to the sensor's specifications, the normal operating temperature range is between +2°C and +121°C. Therefore, the experiment started at +120°C and increased the temperature by 10°C increments until a failure occurred. In order to consider only the temperature, an OF-22 oven was utilized. After collecting data for 8 hours, the sensors were placed in normal conditions for 16 hours to minimize fatigue accumulation as much as possible. After confirming that the sensor was operating normally, the temperature was increased, and the experiment was repeated. The experimental sequence is shown in Fig .4. Two sensors were used in the experiment.

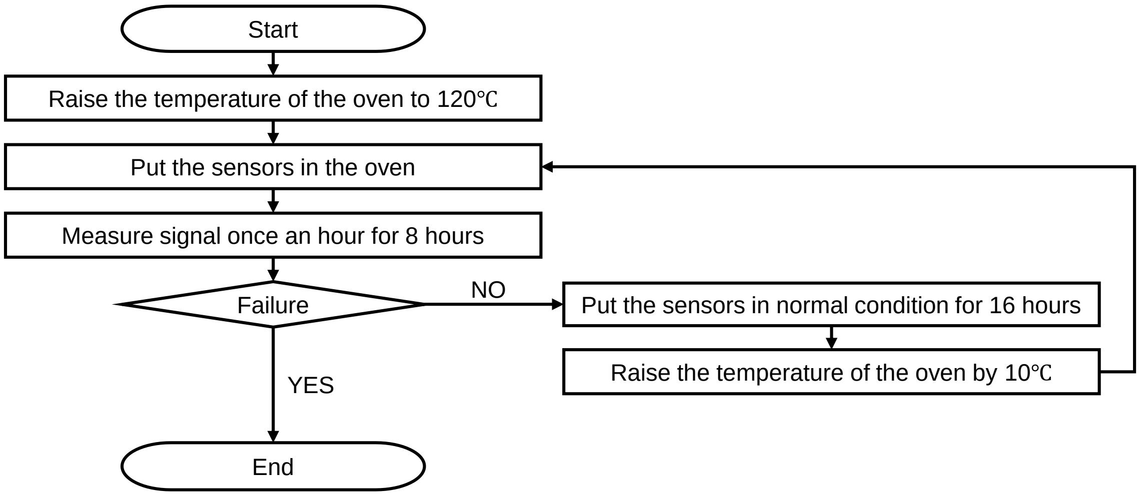

Fig. 4 Flow chart of the experiment

Granite served as the medium for receiving the signal. A steel ball hanging by a thread was dropped to create a consistent impact, and the signal was amplified tenfold by the signal conditioner to be clearly observed. Also, since the frequency range that the sensor can normally receive is 0.5 to 10,000Hz, a low pass filter that receives only signals below 10,000Hz is applied through the signal filter. Finally, the signal was measured through an oscilloscope (Fig. 5).

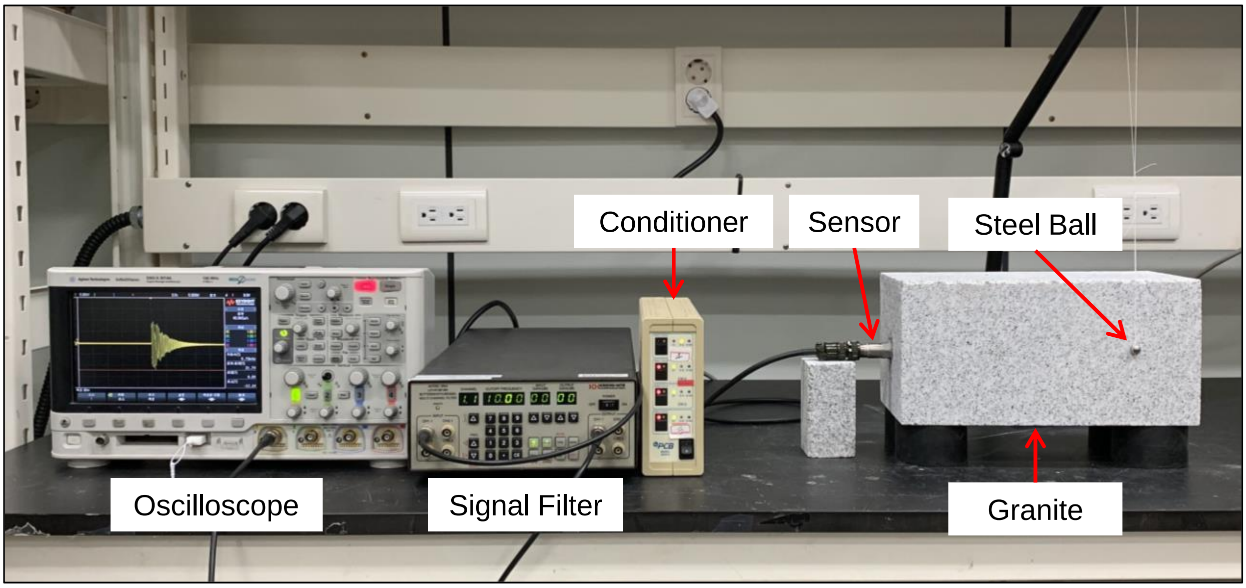

Fig. 5 Experimental equipment

2-3. Experiment result

The main failure mechanism due to high temperature is piezo film transformation. And the main failure mode is poor signal. So, signal comparison is possible using peak value and peak-to-peak value. Consequently, the following failure criteria were established. First, a case in which an error of 20% or more occurs compared to the peak value under normal temperature conditions. Second, a case in which an error of 20% or more occurs compared to the peak-to-peak value under normal temperature conditions. Finally, a case where a signal from the sensor is not received. All values with temperature are shown in the following Fig .6. All values with both sensors were within the normal range up to 140 °C, and no signal was received at 150°C. In other words, at 150°C, no signal is failure mode. It means that the failure mode gets different at 150°C.

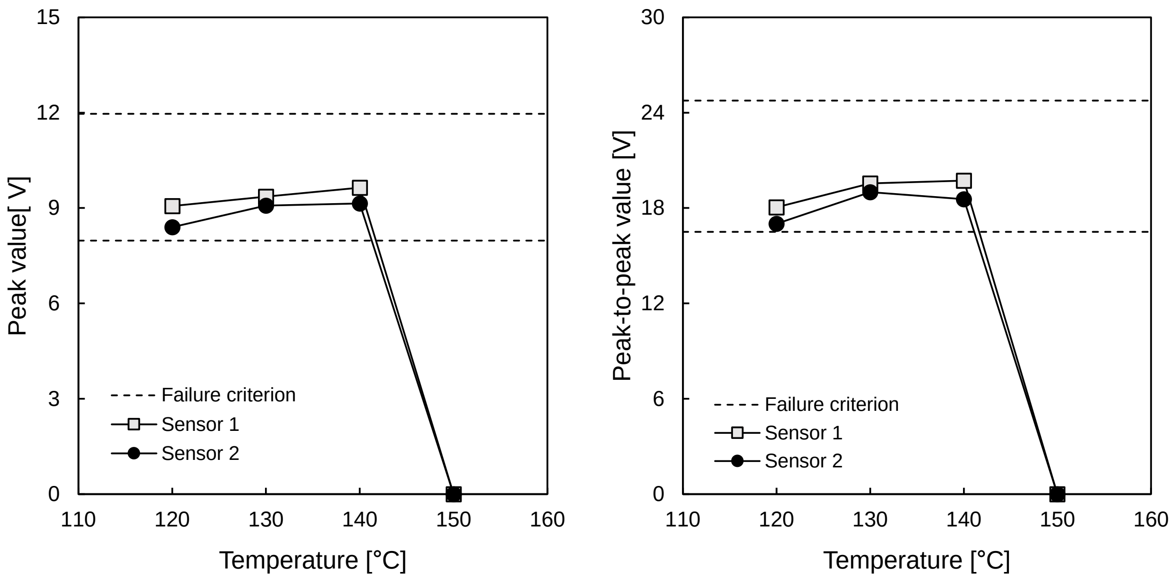

Fig. 6 Peak value and Peak-to-peak value according to temperature

3. CONCLUSIONS

In this study, the basis for assessing the life of the monitoring sensor for the HLW repository was described, and an accelerated life test was presented as a method. The experiment was conducted to design harsh stress levels for an accelerated life test. It was established that both sensors worked normally for all values up to 140°C. No signal was detected at 150°C indicating that 150°C is an operational limit beyond which this sensor cannot operate normally. In other words, the failure mode gets different at 150°C. Therefore, the harsh stress level should be set 140°C or less.

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