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CISCC Countermeasures for Spent Fuel Canisters in Concrete Casks

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ABSTRACT

Aging management of spent fuel is an important issue worldwide. Chloride-induced stress corrosion cracking (CISCC) of welded canisters is particularly important for concrete casks, where it occurs in response to a combination of environmental, material, and residual stress factors. In this paper, we introduce a countermeasure to prevent the occurrence of CISCC by adjusting the flow rate of the cooling air into the concrete cask so that the canister surface temperature does not decrease below 100°C, which is a conservative deliquesce temperature threshold for CISCC occurrence. The flow adjustment device was installed in a cask model, and two tests were conducted under the heat rate conditions corresponding to those of an actual canister. In the first test, the device was operated under a condition where the canister surface temperature was below 100°C to verify whether it could increase the canister surface temperature to above 100°C. In the second test, the heat rate was decreased from a state where the canister surface temperature was above 100°C, to verify whether the device could maintain the canister surface temperature above 100°C. Good results were obtained in both cases. However, in the case of a low decay heat rate of spent fuel after extended dry storage, the temperature of the canister surface may decrease below 100°C even if no air supply is provided. Therefore, in this case, it may be necessary to take measures such as blocking air outlets.

INTRODUCTION

In Japan, if reprocessing is delayed, it is estimated that about 10,000 tU of spent fuel will need to be stored by 2030 [1]. If all this spent fuel is to be stored in casks, 1,000 casks will be needed. At present, only metal casks are used in Japan, but it may be difficult to store spent fuel exclusively in metal casks, and the practical use of concrete cask storage systems, which can be manufactured economically, is expected. In the U.S., 90% of dry storage is in concrete casks, and the Nuclear Regulatory Commission has received license applications for two consolidated interim storage facilities in 2016 and 2017 (https://www.nrc.gov/waste/spent-fuel-storage/cis.html). When concrete casks are introduced in Japan, there is a concern about the loss of containment due to chloride-induced stress corrosion cracking (CISCC) in the canisters because the storage facilities have been built near the coast. In addition, CISCC is recognized as a potential degradation mechanism that requires aging management [2], and its countermeasures are attracting attention worldwide. The environment, materials, and residual stresses are responsible for the occurrence of CISCC; we have been investigating environmental countermeasures. Takeda and Saegusa [3] have previously devised a countermeasure to reduce the salt particles in the cooling air flowing into the concrete cask; the present paper presents a countermeasure to prevent the occurrence of CISCC by adjusting the flow rate of the cooling air flowing into the concrete cask so that the temperature of the canister surface does not decrease below 100°C, which is the conservative deliquesce temperature threshold for CISCC occurrence [4].

TEST APPARATUS

Figure 1 shows a flow adjustment device that regulates the amount of cooling air flowing into the cask. The temperature TS of the lower portion of the canister surface is measured, and the temperature information is sent to the temperature controller. If TS is lower than TP, which was set in the temperature controller previously, the power is turned on and the pump starts to draw air into the cylinder. Then, the silicon plate at the end of the rod is pulled up, and the air supply port is closed. Therefore, the flow of cooling air is stopped, and the canister temperature increases. On the other hand, if TS is higher than TP, the pump is turned off and air enters the cylinder. Therefore, the piston descends under its own weight, the air supply inlet is opened, and the flow rate increases. As a result, the canister is cooled. The advantages of this device are, first of all, that it can be used anywhere a thermocouple can be installed. Second, changes in air supply temperature do not interfere with the control of the flow adjustment device. Furthermore, it has a fail-safe design, as the power supply is turned off when the canister becomes too hot.

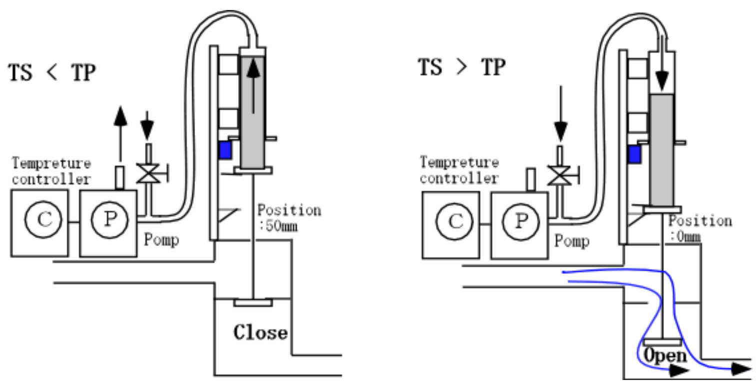

Fig. 1. Flow adjustment device

We performed tests using a cask model to demonstrate whether the flow rate of cooling air could be regulated and the canister temperature maintained at the previously set value by using the flow adjustment device. The 1/4.5-scale cask model used is shown in Fig. 2. There is a channelling gap between

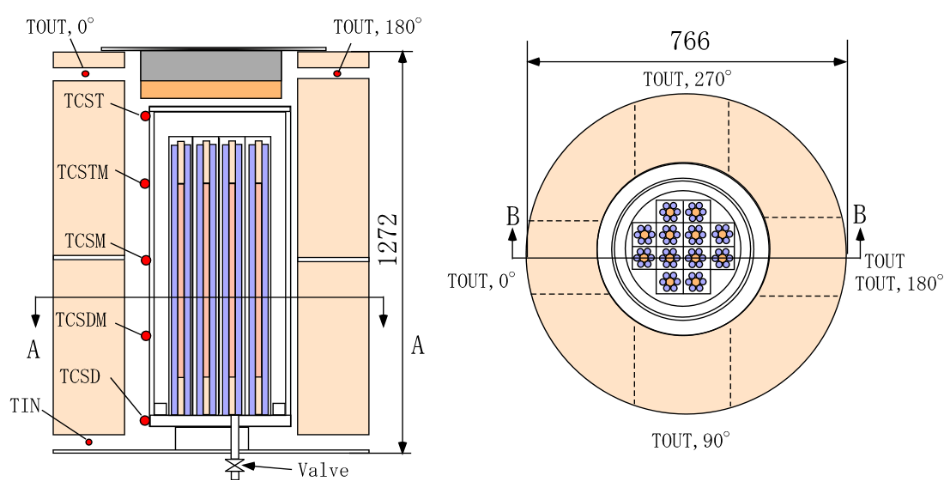

Fig. 2. 1/4.5-scale cask model. TIN, air inlet temperature; TOUT, outlet temperature; TCSDM, canister surface temperature at mid-point of lower portion of the canister.

the cask model and the canister model for air flow with four inlets and four outlets at the bottom and top of the cask model, respectively. Twelve heaters that simulate the spent fuel assemblies are installed within a basket in the canister model. In the test, the surface heat flux of the model canister was set to be the same as that of the actual canister. Since the heat capacities of the actual and model canisters are different, the response time for temperature control is also likely to be different. The tests are therefore conducted to demonstrate the feasibility of the temperature control by using the flow adjustment device.

Figure 3 shows a diagram and a photograph of the 1/4.5-scale cask model with the flow adjustment device installed near the bottom air inlet of the cask model. The device and the flow velocity measurement unit were installed at the air inlet on the 0° side of the cask model shown in Fig. 2, and the other air inlets were completely closed. In actual casks, the flow adjustment device would be installed when the decay heat rate of the spent fuel in the canister becomes small after extended dry storage. In such a situation, it may be necessary to install the flow adjustment device in one of the four air inlets and close the other three air inlets.

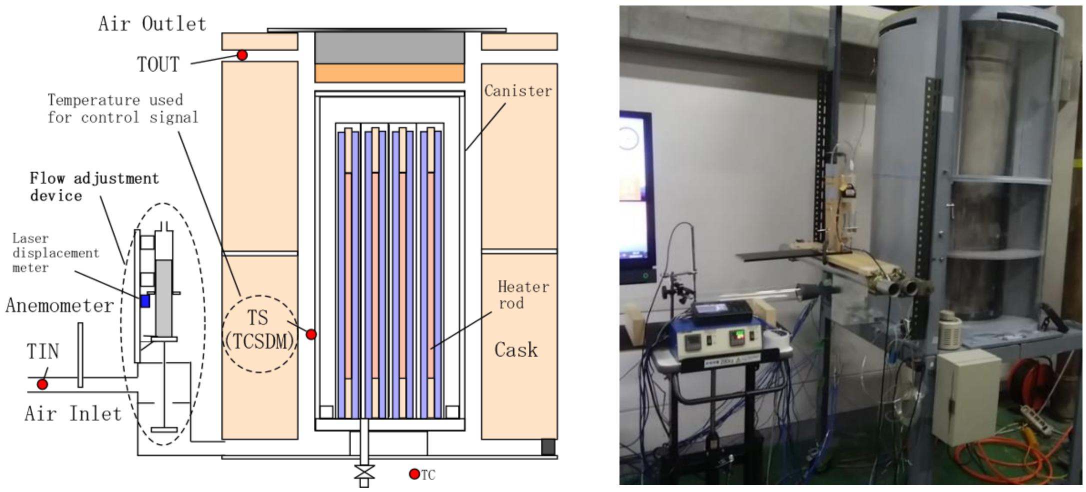

Fig. 3. Installation drawing and photograph of the air inlet of the flow adjustment device. TIN, TOUT, and TCSDM (TS) are defined in Fig. 2.

AS ONE TR-KN-T was used as the temperature controller. The minimum setting unit is 1°C. K-type thermocouples with a diameter of 0.5 mm were used for temperature measurement, and a hot-wire anemometer, SATOTECH AM-4214SDJ, was used for flow velocity measurement. The laser displacement meter KEYENCE IL-S100 was used to measure the displacement of the open/close valve of the flow controller. The measurement range of the displacement is 0–50 mm. 0 mm indicates the state where the valve is fully open, and 50 mm indicates the state where the valve is fully closed. The data logger used was a Graphtec 840GL, and the sampling time was set to 1 sec.

TEST CONDITIONS

The test conditions are shown in Table 1. The relationship between the storage period and heat rate of the actual canister is shown in Fig. 4. Since the purpose of this study is to prevent SCC, the test conditions included a low heat rate, where the temperature of the lower part of the canister may be below 100°C. In previous studies [1], it was reported that the surface temperature of the canister was below 100°C when the decay heat rate of the actual canister was 10 kW or less, and this heat rate was used as a reference. The heat rate in the test was determined by matching the canister surface heat flux with that of the actual canister.

In Case 1, the test was conducted at 424 W. The TCSDM, which indicates the temperature on the canister surface, was 97℃, which is below 100℃. As shown in Fig. 4, in the actual canister, the heat rate is 8.6 kW, which corresponds to a storage period of 48 years. From this state, the set temperature (TP) of the temperature controller was set to 101°C about one hour after the start of measurement. Therefore, we verified whether the canister surface temperature was kept above 100°C by the flow adjustment device, and furthermore, that it did not cause excessive temperature rise. In Case 2, when the heat rate was set to

456 W, the canister surface temperature was 102.5°C. From this state, the heat rate was reduced to 390 W. In this test, the TP was set previously to 101°C. In the actual canister, the heat rate has decreased from 9.2 kW to 7.9 kW, simulating the extension of the storage period from 43 years to 53 years. Therefore, the canister temperature gradually decreases. For this situation, we verified whether the flow adjustment device would work properly and keep the canister surface temperature above 100°C.

Table 1: Test conditions

Case No.	Heat rate(W) (Model)	TP(℃)	Remarks Heat rate(kW) (Actual Canister)
Case 1	424	→101	8.6
Case 2	456→390	101	9.2→7.9

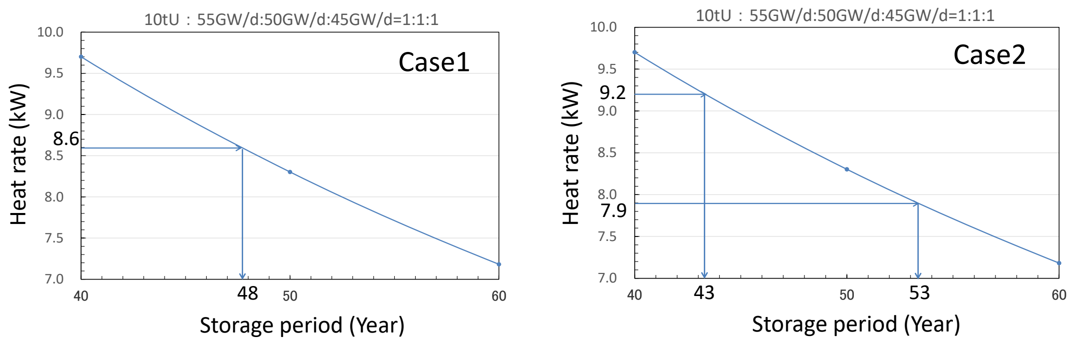

Fig. 4. Relation between storage period and decay heat rate in an actual canister.

TEST RESULTS

A flow adjustment device was installed at the air inlet of the cask model, and tests were conducted to confirm whether the canister surface temperature could be maintained from lower to higher than the set temperature, and whether the canister surface temperature could be maintained at the set temperature when the temperature gradually decreased from the higher temperature.

1) Case 1

The heat rate was set to 424 W. The air inlet with the flow adjustment device was fully opened and left to reach a steady state. Figure 5 shows the relation between the TCSDM, the flow velocity, and the displacement of the valve. At the start of the measurement, TCSDM was 97.0°C, which is below 100°C. The flow velocity was about 40 cm/s, and the position of the valve was 0 mm, indicating that the air supply port was fully open. From this state, about one hour later, the temperature controller was set to 101°C. Immediately after the setting, the displacement of the valve registered as 50 mm, which indicates that the air supply port is fully closed. The flow velocity decreased to 0 cm/s. The TCSDM gradually increased and after about 9 hours, the valve started to operate and the flow velocity was found to fluctuate between 0 cm/s and 40 cm/s. The TCSDM was maintained at 100.5°C. The temperature did not reach 101°C, which is the set temperature, because the minimum unit of the temperature controller's set value is 1°C, and the attained temperature has a tolerance of ± 0.5°C for the set-point temperature. The spike in flow velocity between 1 hour and 9 hours was caused by the temporary opening of the valve as a result of noise. Starting 9 hours later, a flow velocity corresponding to the displacement of the open/close valve was observed. Figure 6 shows the canister surface temperature distribution, and it was shown that by activating the flow adjustment device, the canister surface temperature could be raised above 100°C even in areas where the temperature was below 100°C.

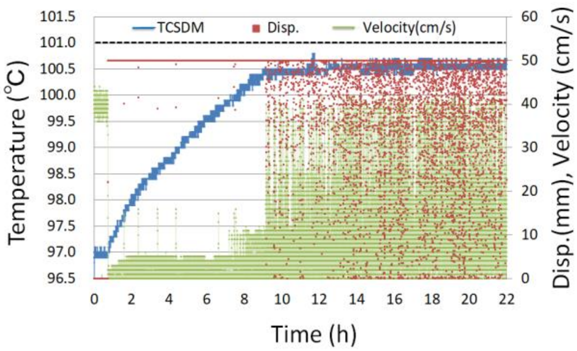

Fig. 5. Relationship between TCSDM, displacement, and flow velocity (Case 1)

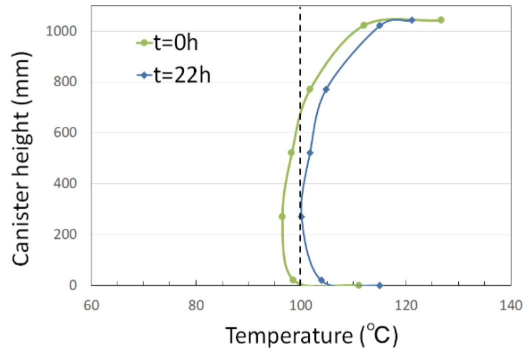

Fig. 6. Canister surface temperature (Case 1)

Figure 7 shows the relation between TCSDM and the air supply temperature (TIN). Fluctuations in TIN were observed, but they did not affect TCSDM. In other words, the flow adjustment device operates to keep the monitored temperature, TS (in this case, TCSDM), at a constant value (TP), so it automatically adjusts the flow rate accordingly even if the TIN fluctuates. Figure 8 shows the relation between the displacement of the valve and the exhaust temperature (TOUT). It can be seen that the TOUT (0°) dropped for about two hours immediately after the valve was closed, but then recovered to the original temperature. The reason for the temperature drop is thought to be that the cooling air flow from the air inlet was eliminated and some of the outlets experienced reverse flow, causing outside air to flow in through the air outlets.

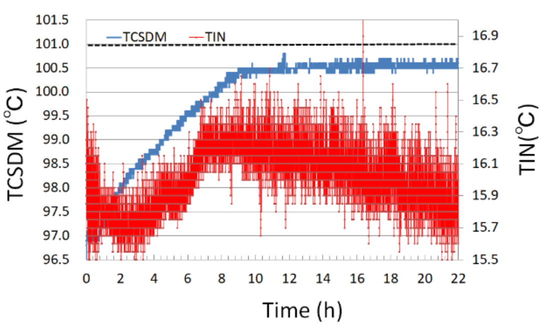

Fig. 7. Relation between TCSDM and TIN (Case 1)

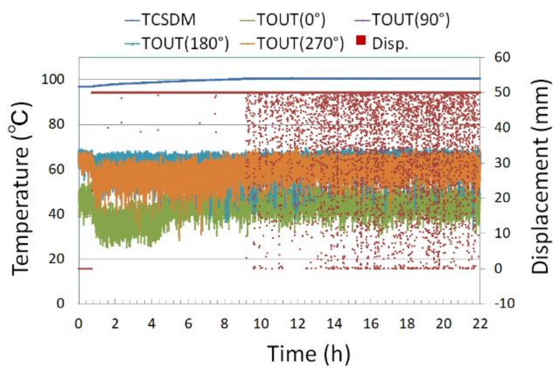

Fig. 8. Relation between TCSDM and TOUT (Case 1)

2) Case 2

The heat rate was changed to 390 W after reaching steady state at 456 W. Figure 9 shows the relationship among TCSDM, flow velocity, and the displacement of the open/close valve. At the beginning of the measurement, the displacement of the valve was 0 mm, i.e., fully open, and the flow velocity was about 40 cm/s. The TCSDM was 102.5°C, which is higher than 100°C. From this state, the TCSDM began to decrease gradually because of the rapid decrease in heat rate The set temperature (TP) was 101°C, but it can be seen that the control started at around 101.5°C. It can be seen that the open/close valve closed more and more frequently, and after 7 hours of measurement, the valve was almost completely closed and the flow rate was zero. In this condition, the TCSDM maintained a constant value of 100.5°C, indicating the limit of temperature maintenance by flow control. After this time, if the heat rate continues to be low, the TCSDM will also decrease further. Therefore, if the canister surface temperature is below 100°C even with the air inlets fully closed, the air outlets must also be fully closed to prevent the intake of outside air, and the heat of the canister can be removed only by the heat conduction effect from the concrete cask, or one can use a heat removal device that bypasses the air inlet and air outlet. In that case, there would be no more salt flowing into the cask, and thus no more factors causing CISCC. Figure 10 shows the canister surface temperature distribution immediately after the start of measurement and after 7 hours, indicating that the minimum temperature of the canister surface is maintained at 100°C.

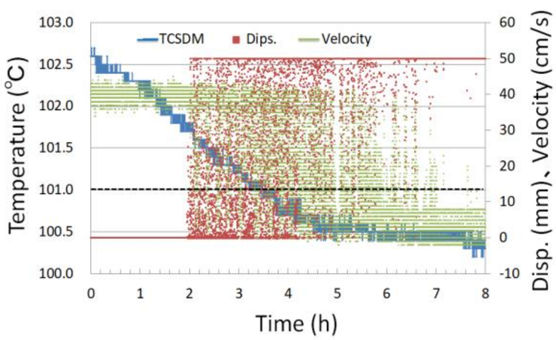

Figure 9. Relationship between TCSDM, displacement, and flow velocity (Case 2)

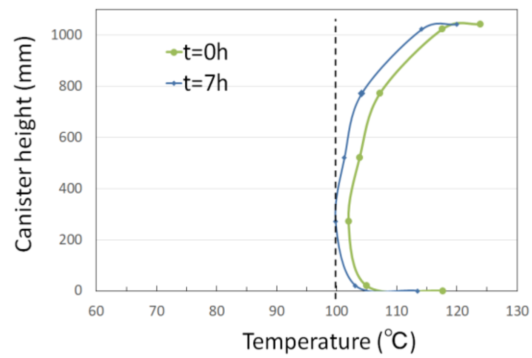

Figure 10. Canister surface temperature (Case 2)

Figure 11 shows the relation between TCSDM and TIN, and it can be seen that TCSDM is temperature-controlled regardless of the change in TIN. Figure 12 shows the relation between the displacement and TOUT. It can be seen that as the heat rate decreases, TOUT also gradually decreases.

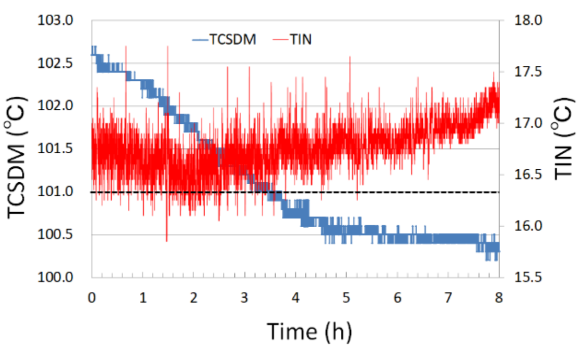

Fig. 11. Relation between TCSDM and TIN (Case 2)

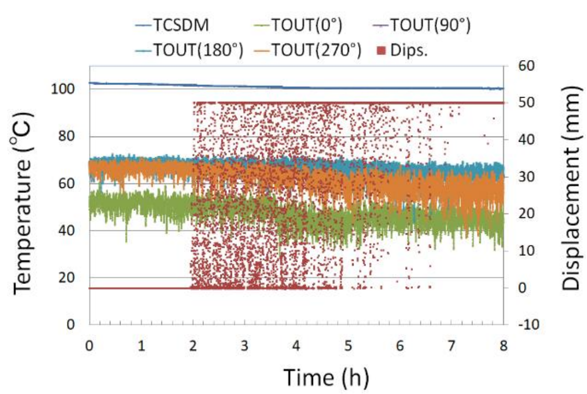

Fig. 12. Relation between TCSDM and TOUT (Case 2)

SUMMARY AND CONCLUSION

A countermeasure that prevents the occurrence of CISCC by adjusting the flow rate of the cooling air into the concrete cask has been developed and its feasibility demonstrated by using a 1/4.5-scale model cask. The flow adjustment device was installed alongside the 1/4.5-scale model cask that automatically adjusts the flow rate of the cooling air into the flow channel between the canister and cask to maintain the canister surface temperature above 100°C, which is a conservative deliquesce temperature threshold for CISCC occurrence. Two tests were conducted under the heat rate conditions corresponding to those of an actual spent fuel canister after long-term dry storage. In the first test, the flow adjustment device was operated under a condition where the canister surface temperature was below 100°C to confirm whether the device could increase the canister surface temperature to above 100°C. In the second test, the heat rate was decreased from a state where the canister surface temperature was above 100°C, to verify whether the device could maintain the canister surface temperature above 100°C. Good results were obtained in both cases. However, in the case of a low decay heat rate of spent fuel after extended dry storage, the temperature of the canister surface may decrease below 100°C even if no air supply is provided. Therefore, in this case, it may be necessary to take measures such as blocking air outlets or using a heat removal device that bypasses the air inlet and air outlet.

The Central Research Institute of Electric Power Industry (CRIEPI) and Argonne National Laboratory (Argonne) have a joint research agreement on the development and demonstration of a detection method for gas leakage from canisters based on temperature information using the Remote Area Modular Monitoring (RAMM) for canister surface temperature measurement (TM). RAMM-TM is a customized device developed by Argonne for the gas leakage experiments conducted at CRIEPI by using a 1/4.5-scale model cask. Demonstration of performance of RAMM-TM in the initial set of canister gas leakage experiments can be found in refs. [5, 6], along with development of scenarios and timelines for the management of radiological consequences of gas leakage from spent fuel canisters [7]. Since the canister surface temperatures, such as TCSDM/TS, are already monitored by RAMM-TM, implementation of the temperature control setpoint (TP) for the flow adjustment device into RAMM-TM should be relatively straightforward.

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