

HEAT REMOVAL TESTS FOR THE HIGH PERFORMANCE VAULT STORAGE SYSTEM OF SPENT NUCLEAR FUEL

M. Oda*, M. Shimizu*, N. Kumagai*, H. Kanai**, M. Tanabe**

*Nuclear Fuel Cycle Group, Power & Industrial Systems R&D Division, Hitachi, Ltd.

7-2-1 Omika, Hitachi, Ibaraki, 319-1221 Japan

Tel: +81-294-53-3111, Fax: +81-294-53-7310, E-mail: oda@erl.hitachi.co.jp

**Hitachi Works, Hitachi, Ltd.

3-1-1 Saiwai, Hitachi, Ibaraki, 317-8511 Japan

ABSTRACT

A new concept has been proposed for a vault type spent fuel storage system which can achieve a high storage density of 0.7MTU/m^2 . Two canisters, with 10 - 40 BWR spent fuel assemblies each, are vertically inserted in line into a storage tube. The storage room is radiologically shielded and an air flow separation baffle is installed horizontally in the middle of the area holding the storage tubes. The cross flow air generated by the stack effect removes decay heat from the spent fuel.

Heat removability in the storage room is one of the most important points for realizing this system. Small model tests and thermal hydraulic analysis were performed to clarify the air flow distribution in the storage room. Air flow rate and pitch distance of heaters were chosen as experimental parameters. The analysis model was confirmed by test data. The analysis model and knowledge acquired from the heat removal tests were applied to improve the air flow passage in the storage room so that the structural concrete temperature remains below 65°C during the storage period and the pitch distance of the storage tubes can be rationalized to increase the storage density.

INTRODUCTION

Spent nuclear fuels will eventually be routinely reprocessed in Japan. However the reprocessing capacity of the facility currently under construction is not enough to treat all the spent nuclear fuels generated from the nuclear power plants. This will result in a temporary lack of spent nuclear fuel storage capacity at reactor sites, so that construction of large scale independent interim storage facilities is desired both at reactor sites (ARs) and away from them (AFRs) before 2010.(1)

We have proposed a new spent nuclear fuel storage system which is suitable as an independent storage facility ARs and AFRs. Dry storage systems have received much attention as an interim storage system. Because natural convection of air removes decay heat from the spent nuclear fuel in the dry storage systems, incidental equipment is reduced in amount as compared to wet storage.

There are 4 types of dry storage systems; metal cask, concrete cask, silo and vault. A vault type storage system has the highest storage density and is suitable for storing a larger quantity of

spent nuclear fuels. Design criteria for dry storage are listed in Table 1. The criticality requirement is not so difficult because there is no water around the fuels in dry storage, but heat removal and shielding are more difficult than for wet storage.

Table 1 Design criteria of dry storage

Category	Items	Allowable level
Heat removal	Maximum temperature of fuel claddings	$\leq$ Temperature which causes 1% creep deformation of claddings after a defined storage period
	Structural concrete temperature	$\leq 65^{\circ}\text{C}$ (Normal) $\leq 90^{\circ}\text{C}$ (Local)
Shielding	Dose limit for the public exposure	$\leq 1000\ \mu\text{Sv/year}$
	Dose limit in the control area	$\leq 300\ \mu\text{Sv/week}$
Criticality	Effective multiplication factor of neutrons	≤ 0.95

SYSTEM DESCRIPTION AND SUBJECT

The facility for the high performance vault type storage system has a modular structure. Each module is separated by a wall and has an independent air inlet and outlet. The major components of a module are shown in Fig.1. In this system, spent nuclear fuel is at first inserted into the high capacity canister (10-40 BWR fuel assemblies per canister) and canisters are then welded shut. Two canisters are stored on top of each other in a storage tube. Storage tubes are placed vertically in the storage room. The storage room is separated horizontally into two parts by a separation baffle. In line placement of canisters allows a much higher storage density of $0.7\ \text{MTU/m}^2$ to be achieved.

The stored fuels contain radioactive elements (e.g. fission products) . The canisters seal in these radioactive elements, keeping them inside the canisters even if the fuel cladding has failed. But the canister does not provide radiological shielding. Radiation shielding is provided by the handling machine before the canister is inserted into the storage tube and by steel reinforced concrete walls around the storage room after placement there.

Decay heat from the fuels stored in the canister is removed by air flow outside the storage tubes. The air flow is driven by the stack effect. A stack about 30 meters high is located at the center of the facility. Flow in the storage room is horizontal and crosses a array of canister storage tubes. This heat removal system has two advantages. (1) No external power supply for ventilation in the storage room is needed because the source of air flow is the decay heat itself. (2) The horizontal flow style has a low flow resistance which contributes to stack height reduction.

On the other hand, flow distribution in the storage room is complicated and strongly affected by air inlet and outlet shapes, stack size, quantity of heat in the canister and so on. So technology to estimate the heat removability in the storage room precisely and control the temperature of the structural concrete under 65°C are critical. We performed small model tests and thermal hydraulic analysis to clarify the air flow patterns in the storage room for this system..

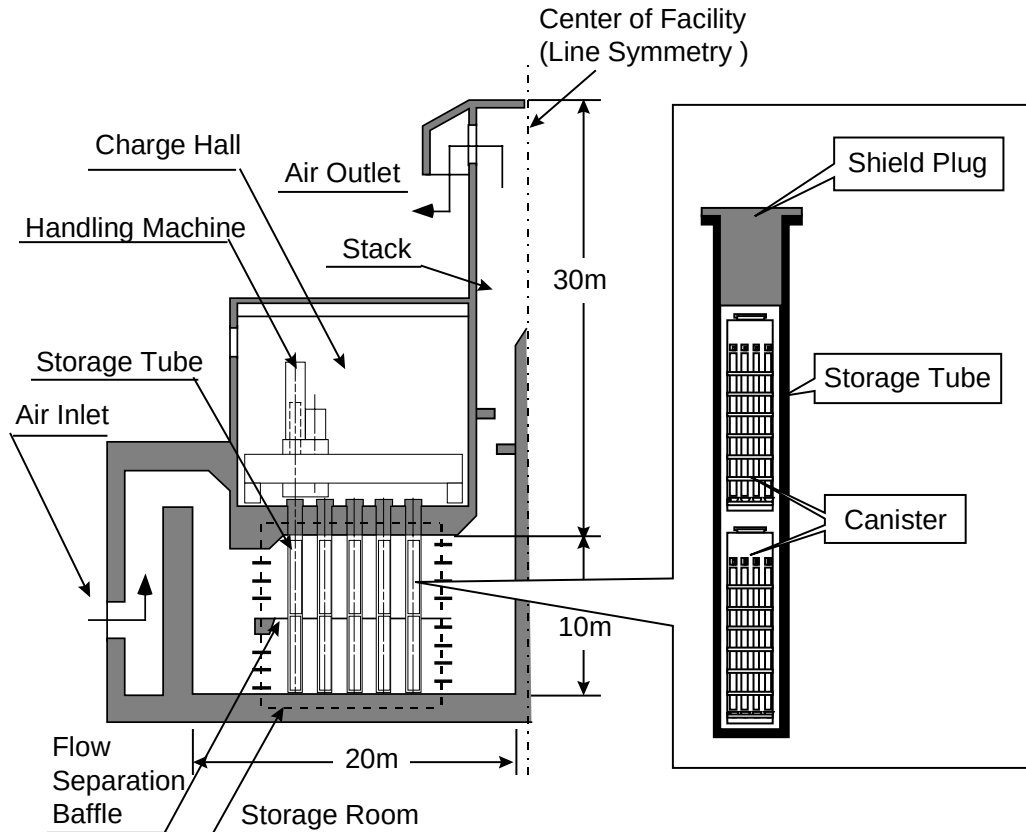


Fig.1 Major components of the high performance vault type storage system (Primary Design)

EXPERIMENTAL PROCEDURE

The experimental equipment, shown in Fig.2, consisted of cylindrical heaters, flow separation baffle, draft fan and casing. The cylindrical heater and dummy tube corresponded to a storage tube with two canisters filled with spent nuclear fuel. There were two heating areas for the cylindrical heaters. The range of each heating area corresponded to the heat generating region of spent nuclear fuel assemblies in the canister. The dummy tube maintained a symmetrical flow on the horizontal plane in the casing. The flow separation baffle, which was made of heat insulating plate, was placed horizontally in the middle of the heaters array. A draft fan was in place of the stack to make it easy to change the air flow rate; this would correspond to changing the stack height in the real size facility. We confirmed experimentally that the draft fan produced the same flow as the stack. The casing was covered by a thermal insulator because heat passing through the casing was irregular and the accuracy of the temperature control inside the casing would be less without it.

Main specifications of the experimental equipment are shown in Table 2. The scaling factors of this equipment was approximately 1/4 in size and combinations of heater power and air flow rate were selected with a view to reproducing air flow patterns in the actual sized storage room.

Testing conditions are shown in Table 3. Arrangement of the heaters could be the regular triangular array or distorted triangular array in the air flow direction. For the former, the pitch distance in the Y-direction (perpendicular to the main flow direction) was $1.6d$, where d is the diameter of the cylindrical heater, and in the X-direction (main flow direction) it was $1.4d$. For the latter array, pitch in the X-direction was $1.1d$. (X and Y are indicated in Fig.2.)

The temperature distribution in the casing was measured with K type sheathed thermocouples. Six thermocouples were set in the longitudinal direction at each of eleven measurement points along the air flow direction. Air inlet and outlet temperatures were also measured to check the heat balance between generated heat and that removed heat by air.

The total rate of air flow in the casing was measured in both the air inlet and outlet to check for air leakage to and from the casing. An "I" shape hot wire anemometer was used.

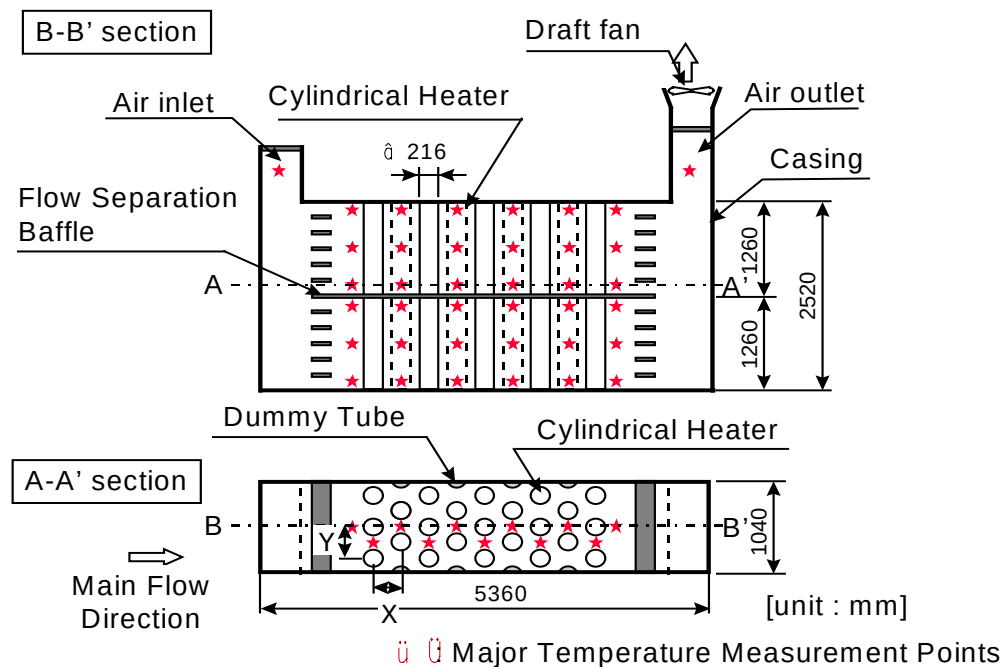


Fig. 2 Experimental equipment for heat removal testing in the storage room

Table 2 Specifications of the testing equipment

Overall size	W: 1040mm, D: 5360mm, H: 2520mm (Inlet and outlet duct excluded)
Heater capacity	Max. 1.6 kW/heater
Number of heaters	23
Air flow rate	Max. 80 m ³ /min
Temperature measuring points	66 (in array section), 84 (42 points each in inlet and outlet)

Table 3 Testing conditions

Case no.	Heat power (kW/heater)	Air flow rate (m ³ /min)	Pitch distance of heaters		Note
			X-direction	Y-direction	
1	1.41	52	1.6d	1.4d	Regular triangular array d : heater diameter
2	1.41	36	1.6d	1.4d	
3	1.41	52	1.6d	1.1d	Distorted triangular array
4	1.41	39	1.6d	1.1d	

RESULT and DISCUSSION

Effect of Air Flow Rate

Air temperature distributions in the casing for two different air flow rates are shown in Fig.3. Case 1 results for high air flow rate are on the left and case 2 results for low air flow rate are on the right. For case 1, air temperature increased with air flow from the inlet to the outlet in both upper and lower sections. But when air flow rate became low, the air temperature increased moving toward the ceiling of the upper section in the casing and a hot spot was generated. It was caused by a change of the flow pattern in the casing. So we carried out a thermal hydraulic analysis to better understand the air flow patterns for the experimental conditions.

We adopted a two-dimensional analysis model; the array of tubes was replaced by a porous medium with an equivalent pressure drop coefficient, area of the air flow passage and overall heat released from the tubes. Fluid (air) density changes with temperature was considered.

The analysis model was verified by comparing the temperature data obtained from the analysis with that from these heat removal test results on both high and low air flow rate conditions. Analysis results had good agreement with test results and air flow rate distributions from the analysis indicated that the stagnation point was generated at the hot spot for the low air flow rate condition.

The cause of the stagnation point was thought to be downward flow in the inlet. When the air flow rate becomes low, the pressure drop in the array of cylindrical heaters (storage tubes) becomes small. So the effect of downward flow in the inlet becomes large, and the air flow rate ratio to the upper section becomes small.

To prevent stagnation, a restraint structure for downward flow was added to the primary design of the facility. Its improvement effect for the small model was confirmed by both experiment and thermal hydraulic analysis. For the actual size facility, we performed thermal hydraulic analysis using the same model with the result that the maximum air temperature was under 65°C even for low flow rate operation.

Effect of Changing the Flow Direction Pitch

Air temperature distributions from the experimental results for the distorted triangular array are shown in Fig.4. Case 3 results for high air flow rate are shown on the left and Case 4 results for low air flow rate are shown on the right. Temperature profiles were almost the same as those for the regular triangular array (Fig.3) except the magnitude in the main flow direction (X-direction).

It is known that the pressure drop in an array of tubes depends on the cross flow velocity of the narrowest section(2). This is valid for the homogenous flow condition in the longitudinal direction, but our experimental results suggest that it is also valid for a slightly complicated flow condition like flow stagnation as generated in the array.

This knowledge was applied to rationalize the pitch distance of the storage tubes. We could increase storage density 20% over than that of the regular triangular array.

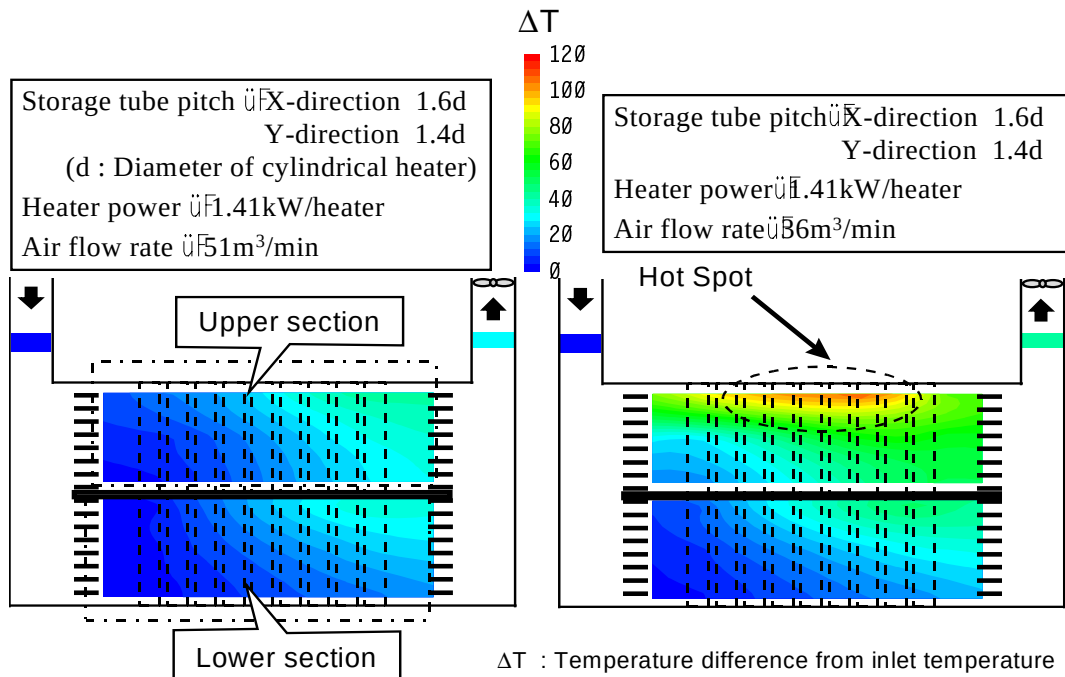


Fig. 3 Air temperature distribution in the array of cylindrical heaters (regular triangular array)

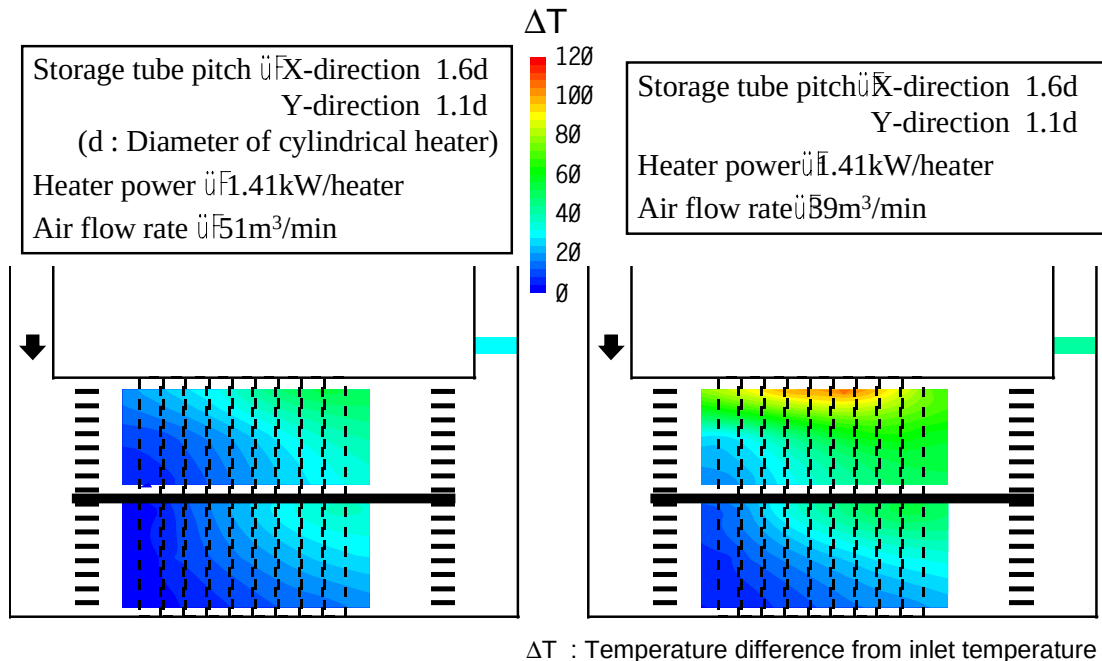


Fig. 4 Air temperature distributions in the array of cylindrical heaters (distorted triangular array)

CONCLUSIONS

We performed heat removal tests using a small model and carried out a hydraulic analysis to characterize the performance of a high density vault storage system. We found the following.

1. The two-dimensional thermal hydraulic analysis model was confirmed on the basis of a comparison of the air temperature distribution from heat removal tests.
2. The heat spot caused by the flow stagnation point was generated when the air flow rate in the storage room became low.
3. The pitch distance in the main flow direction of the storage tubes array could be reduced to at least 1.1d (d = tube diameter) without decreasing heat removability.

This analysis model and knowledge from the heat removal test are being applied to improvement of the air flow passage in the storage room to keep the structural concrete temperature under 65°C during storage period and rationalize the pitch distance of the storage tubes to increase their storage density.

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