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Study on Validation of the Thermal Calculation Method and the applicability of the Confinement Monitoring with Full-scale Mock-up Test of Concrete Cask

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Abstract

We manufactured a full-scale mock-up ventilated concrete cask and carried out thermal experiments under various conditions. All measured temperatures are within each acceptable limit and it is confirmed that the concrete cask has sufficient heat removal capability. Benchmark analyses using a combined thermal calculation method were carried out. At first airflows and temperatures outside the canister were calculated by 3-dimensional thermal-flow analysis. Next, its results were used as the boundary conditions in calculating maximum temperatures inside the canister by 2-dimensional heat transfer analysis. Both calculated results agreed well with the measurements and the validity of the combined method was confirmed.

We newly propose a canister confinement monitoring system. It is based on the relation between the canister inner pressure and the temperature of the canister lid and the pedestal. The validity and applicability of the system is confirmed by the full-scale mock-up experiment results. The conceptual design of the monitoring system is considered and the system can realize low cost, high reliability and easy maintenance.

1. Introduction

Ventilated concrete cask systems have already been made practical for interim storage of spent nuclear fuels in some countries. Some investigations for them are being progressed in Japan. A concrete cask consists of a cylindrical canister with a thin steel shell and an annular overpack with a thick concrete wall as shown in Fig.1. The canister provides the confinement boundary for the contained spent nuclear fuel assemblies (radioactive materials) through the use of redundant seal welded closures by the canister lid and the closure ring. The overpack provides the shielding by concrete and heat removal by natural convection airflows. The cooling air is sucked in from 4 inlet vents at the bottom and goes up between the canister and overpack inner shelll and is exhausted from 4 exit vents at the top. The air pass is also important for shielding ability because the radiation leaks through it by streaming. So it is necessary to demonstrate the heat removal capability and confirm the validity of the thermal calculation method by benchmark calculations to optimize the structure of the air pass including the inlet and exit vents.

Furthermore the confinement integrity of the canister is very important and the reliability for the concrete cask safety can be enhanced if the confinement integrity can be monitored continuously by any measurements.

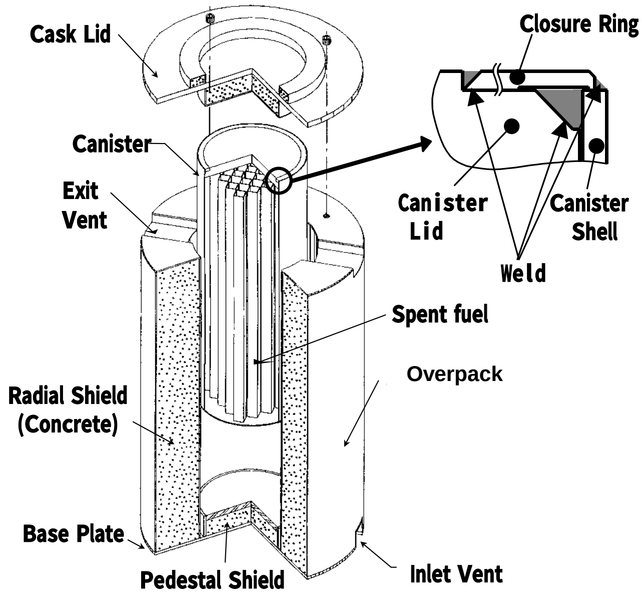


Fig.1 Bird’s Eye View of Ventilated Concrete Cask

Table 1 Major specifications of the mock-up

Item	Specifications
Basket	Material : Borated Aluminum Capacity : 21 fuel assemblies
Canister	Material :Duplex stainless steel Outer Diameter : Approx. 1.65 m
Overpack	Outer Diameter : Approx. 4m Height : Approx. 6m
Total Weight	Approx. 200 ton
Heat Load	max. : 22.5 kW (21 Electric Heaters)
Measurement	Temperatures at over 100 points Pressure in the canister Airflow rates at inlet vent and exit vent

2. Full-scale Mock-up Experiments

We have made a full-scale mock-up concrete cask and carried out thermal experiments to demonstrate its heat removal capability and get benchmark data. Although the concrete cask is based on HI-STORM100 type of HOLTEC international, some structures and materials are changed to satisfy the requirements and needs in Japan. For example, Borated aluminum is used to enhance the heat removal capability in the canister and satisfy lower temperature limits of the spent nuclear fuel cladding than the United States. Duplex stainless steel is used to enhance the corrosion (SCC) resistance during long-term storage.

The full-scale mock-up is basically same as the practical concrete cask and its weight is approximately 200 tons. Electric heaters are used instead of spent nuclear fuel assemblies for heat generation sources and total heat generation can be changed in the experiments. Temperatures at over 100 points were measured continuously by thermocouples and inner pressure in the canister and the airflow rates at the inlet vent and exit vent were also measured in some conditions. Major specifications of the mock-up are shown in Table 1.Various experiments were carried out. Major parameters of these experiments are shown in Table 2. A scene of these experiments is shown in Fig.2. It is an airflow visualization experiment and the cooling airflow by natural convection is observed by using the smoke from a smoke candle settled near an air inlet vent.

Fig.2 A Scene of VariousHeat Removal Experiments (Visualization of Cooling Airflow)

Table 2 Major parameters of these experiments

Item	Normal Condition	Parameter
Heat Generation	21.0 kW	8 to 22.5 kW
Blockage of inlet vent	None	1or 2
Inner Pressure*	Approx. 0 MpaG	Up to 0.3 MPaG
Canister Position	Center in the overpack	Off center Position

*: Inner Pressure depends on the canister temperature

Measured maximum temperatures of major components are shown in Table 3. It shows that all temperatures have sufficient safety margins to each limit in normal condition. Although the temperatures of the basket and canister are hardly affected by the inlet vent blockage, the temperatures of the air at the exit vent and concrete rise about 10 degrees Celsius by the 2 inlet vents blockage. Even so, all measured temperatures are falling within acceptable limits of each material. It is thought that the concrete cask has sufficient heat removal capability[1].

Table 3 Measured Maximum Temperatures of Major Components(21.0 kW)

Unit:Celsius

Conditions	Basket (B-Al)	Canister	Air at Exit vent	Concrete
Normal	199	174	82	74
1 inlet vent Blockage	201	175	88	80
2 inlet vents Blockage	200	176	93	84
Limit	250	250	—	90

Remark : Enviromental temperature is set to 33 degrees Celsius.

3. Benchmark Calculations

The heat removal system of the concrete cask by natural convection airflows is unique and it is difficult to evaluate temperatures in the canister directly by using conventional methods. So we combine 2 calculation methods to evaluate them effectively. In the 1st step, airflow rates and the temperatures outside the canister were calculated by the finite volume computational fluid dynamics code FLUENT[2]. The maximum temperature of the canister outside surface calculated in the 1st step was used as the boundary conditions in calculating

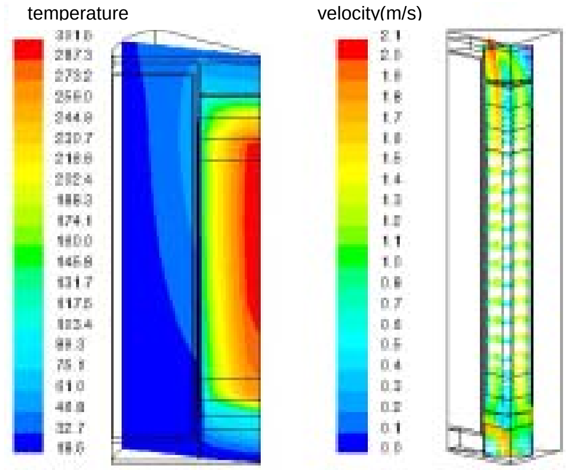
Table 4 Major Calculation Conditions for the Combined Method

Item	1st step (Thermal flow cal.)	2nd step (Heat Transfer cal.)
Heat Generation	22.5, 21.0, 8.1 kW	
Code	FLUENT	ABAQUS
Model	3 dimension (45 ° sector)	2 dimension (90 ° sector)
Boundary Condition	Environmental temperature	Canister maximum tenperature from the 1st step results

temperature inside the canister by the finite element code ABAQUS[3] in the 2nd step.
Benchmark analyses using the combined calculation method were carried out under 3 heat generation rates (22.5, 21.0 8.1 kW) in the normal conditions.

(1) Thermal flow calculation (1st step)

3-dimensional model (45-degree sector) was used to model the airflow pass of the overpack including the inlet and outlet vent correctly. The canister region in the model was homogenized and anisotropic heat conductivity coefficients for axis and azimuthal direction were used in the region to simulate the actual heat transfer in the canister.



(a) Temperature (b) Velocity of Air Flow
Fig.3 Results of Flow Analysis (21.0 kW)

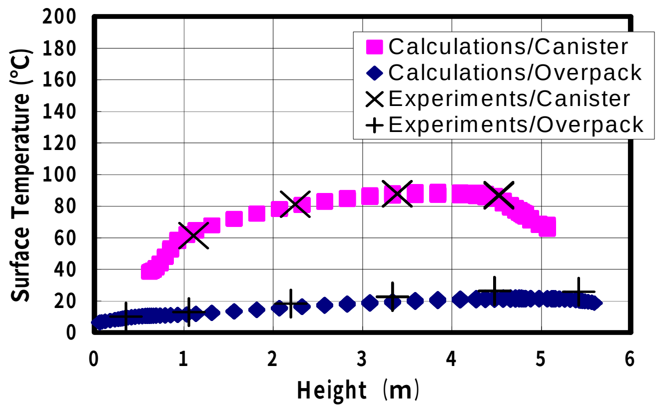


Fig.4(a) Comparison of Surface Temperature between Analyses and Experiments (8.1 kW)

Table 5 Comparison of Canister Surface Temperature between Analyses and Experiments

Unit:Celsius

Heat Generation	22.5kW	21.0kW	8.1kW
Calculation	174	162	90
Experiment	170	159	88

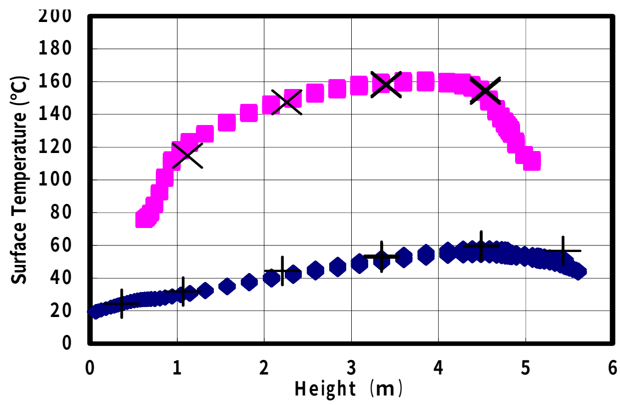


Fig.4(b) Comparison of Surface Temperature between Analyses and Experiments (21.0 kW)

Table 6 Comparison of Airflow rate between Analyses and Experiments

Unit: kg/sec

Heat Generation	22.5kW	21.0kW	8.1kW
Calculation	0.047	0.047	0.031
Experiment	0.047	0.046	0.030

The calculation results of temperature distributions and airflow velocities in the case of heat generation 21.0 kW are shown in Fig.3. It shows that air between the canister and overpack inner shell is heated from the canister and goes up and transfers its heat to the overpack. And the comparison of axis temperature distributions of canister and overpack between the measurements and calculations are shown in Fig.4. Furthermore, maximum temperatures and air low rates are shown in Table 5, 6.

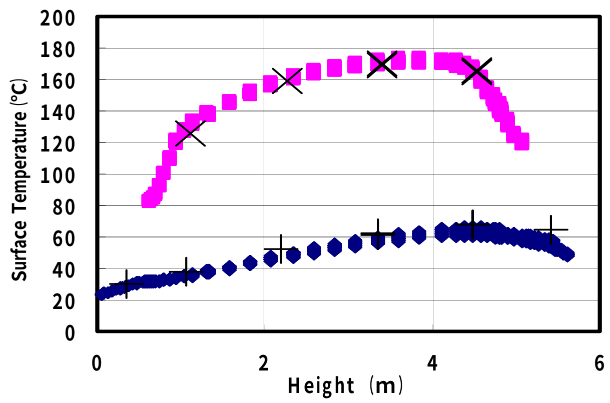


Fig.4(c) Comparison of Surface Temperature between Analyses and Experiments (22.5 kW)

Fig.4 and Table 5 show that the calculated temperatures agree with the measurements very well under these heat generation rates. Table 6 shows very good agreement between the calculation results and measurements of the airflow rates.

(2) **Heat transfer calculation (2nd step)**

Temperatures in the canister were calculated in the 2nd step. In the calculations, a 2-dimensional slice model (90-degree sector) was used to simulate the heat transfer pass (basket and support structures made of aluminium) in detail. Each fuel assembly region was homogenized and the natural convection effects by Helium gas in the canister were ignored. The boundary condition at the canister outside surface was based on the thermal flow calculation results in the 1st step.

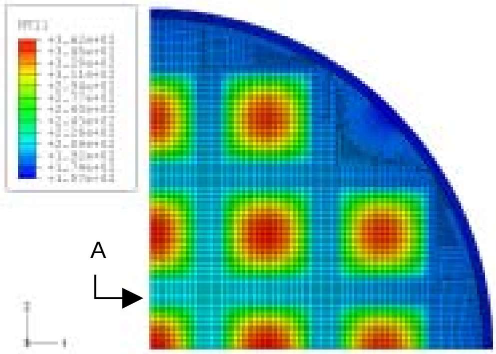


Fig.5 temperature distribution in the canister (21.0 kW)

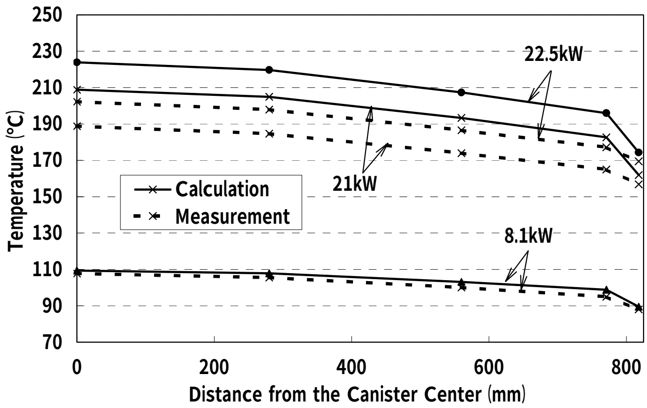


Fig.6 Comparison of Basket Temperature between Analyses and Experiments (at section A-A)

Table 7 Comparison of Basket Temperature between Analyses and Experiments

Heat Generation	22.5kW	21.0kW	8.1kW
Calculation	224℃	209℃	109℃
Experiment	202℃	189℃	108℃

The calculation results of temperature distribution in the canister in the case of heat generation 21.0 kW is shown in Fig.5. The comparison of temperature distribution between calculations and experiments along a basket plate (section A-A in Fig.5) is shown in Fig.6 and the maximum temperatures of the basket are shown in Table 7. According to Fig.6, the calculation results agree with the measurements very well in the case of the low heat generation (8.1kW), but calculation results are a little higher than the measurements in the case of high heat generations (21.0 and 22.5 kW). Although the temperature distribution trends of calculation and experiment agree well in the central region, large discrepancy is shown at the edge of the canister (near 800cm in Fig.6). It is thought that the discrepancy is caused by the calculation model of a gap between the basket and canister shell. The gap is modelled uniformly in the circumference in the calculation, but it is thought that some parts of the basket touch with the canister shell by thermal expansion of the basket in the experiments. So the effective heat conductivity of the gap in the experiments gets much higher than the calculations.

But in all cases the calculation can get valid or slightly conservative results from the experiments by using this combined calculation method. So it is thought that the combined calculation method is valid and sufficient applicable for the concrete cask.

4. Confinement Monitoring System

It is thought that any continuous confinement monitoring systems aren't necessary because redundant seal welded closures of the canister lid are highly reliable. However, from the public acceptance viewpoint, if the canister confinement integrity can be confirmed continuously by a monitoring system, it offers high reliability for the public. Accordingly, we newly propose a simple confinement monitoring system based on the relation between the canister inner pressure and the temperatures of the canister lid and pedestal.

(1) **Principle**

As high pressure Helium gas (up to about 0.3 MPaG) is enclosed in the canister to enhance heat removal capability, Helium gas circulation is formed naturally in the canister as shown in Fig.7. Namely, Helium gas is heated up in the center of the canister and it goes up to the top region. The heated Helium gas transfers its heat to the canister, especially the canister lid and cooled Helium gas goes down along the canister shell in the circumference. If the confinement integrity is broken and the Helium gas leaks from the canister, the effect of the circulation becomes weak and the lid temperature is expected to fall.

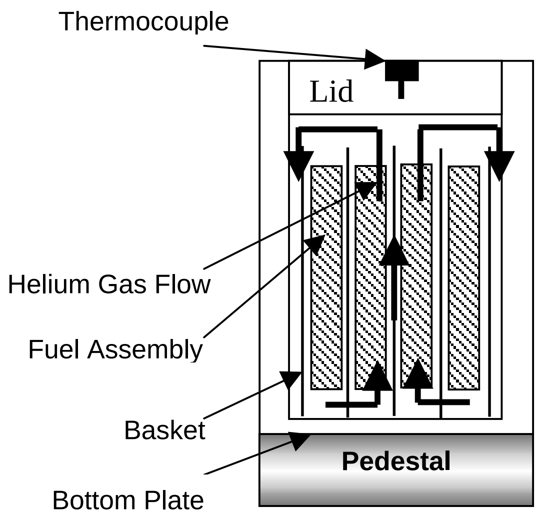


Fig.7 Image of Helium Gas Flow in the canister

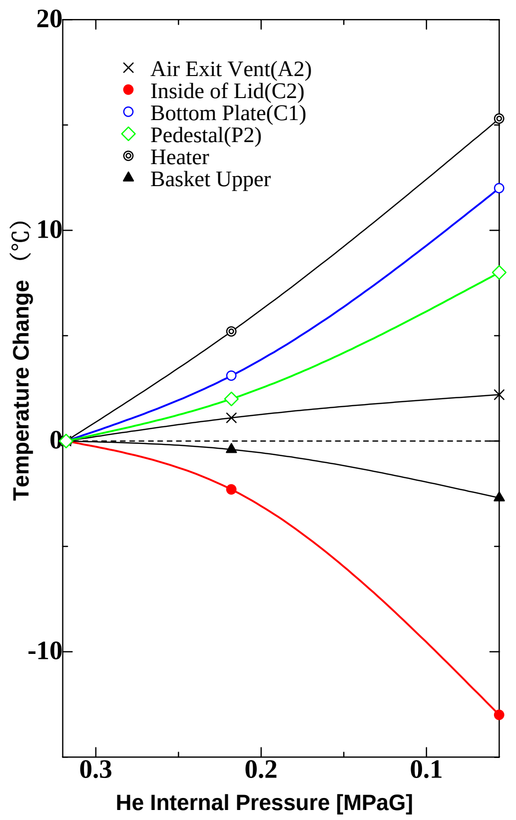


Fig.8 Relation between Major temperatures and He Pressure in the canister

(2) **Validity**

The validity of the proposed monitoring system was shown in the relationship between the temperatures in the concrete cask and the Helium gas inner pressure which were measured in the above full-scale mock-up experiments

(a) Effectiveness

The relation between Helium inner pressure and the major temperatures is shown in Fig.8 and Table 8. Fig.8 shows that the lid temperature goes down according to the drop of the canister inner pressure and the temperature at the canister bottom plate goes up on the contrary. It is because the Helium circulation in the canister weakens by the inner pressure drop and the transferred heat from the Helium gas to the canister lid falls. The temperature at the canister bottom plate rises in the opposite effects.

Furthermore monitoring a temperature difference dT1 (see Table 8) between the lid and bottom plate is more effective than each temperature to detect the Helium pressure change. The change of the temperature difference dT1 is about twice as large as the change of the each temperature and the change is 25 degrees Celsius when the Helium inner pressure drops from 0.32 to 0.06 MPaG in Table 8.

But it is thought that it is difficult to measure the canister bottom plate temperature directly in view of the practical cask handling. So we think the temperature at the top of the pedestal shielding (see Fig.1) can be used instead of the bottom plate temperature because both behaviours of the temperature changes are similar though the temperature change using the pedestal temperature dT2 is a little smaller than dT1 as shown in Table 8. It is thought that the temperature difference is enough to detect the inner pressure change.

Additionally it is expected that monitoring 2 temperatures (lid and pedestal) is highly reliable. Namely, even if a monitoring device is broken, for instance, we can judge it by the other temperature change.

Table 8 Relation of Helium Inner Pressure and Major Temperature

（Environmental Temperature：20℃）

case	Heat Load [kW]	He Pressure [MPaG]	Inside Lid(C2) [℃]	Bottom Plate (C1) [℃]	Pedestal (P2) [℃]	dT1 (C2-C1) [℃]	Change of dT1 [℃]	dT2 (C2-P2) [℃]	Change of dT2 [℃]
a	21	0.056	158.1	114.6	81.2	43.5	-25.0	76.9	-21.0
b	21	0.218	168.8	105.7	75.4	63.1	-5.4	93.4	-4.5
c	21	0.318	171.1	102.6	73.2	68.5	0.0	97.9	0.0

(b) Response

It is important for the safety to detect the change of canister inner pressure as soon as possible. The temperature transition caused by the Helium inner pressure change is shown in Fig.9. dT2 in Fig.9 is monitoring value in the system and it means temperature difference between the lid and pedestal. Fig.9(a) shows that the temperature difference dT2 starts to fall gradually just after the Helium inner pressure sharply drops from 0.32 to 0.06 MPaG. On the contrary, Fig.9(b) shows that the temperature difference starts to rise gradually just after the Helium inner pressure sharply rises from 0.06 to 0.22 MPaG. As in both cases the trends of the dT2 are different clearly from the other temperatures including inlet vent temperature. It is thought that the canister inner pressure change can be detected soon after the inner pressure changes.

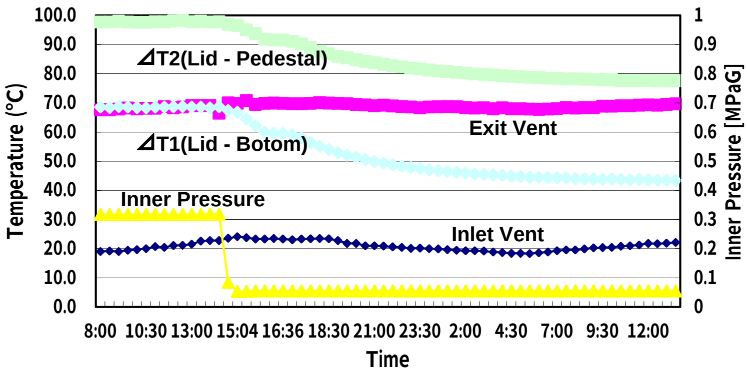


Fig.9(a) Temperature Response by Inner Pressure Change (from 0.32 to 0.056 MPaG)

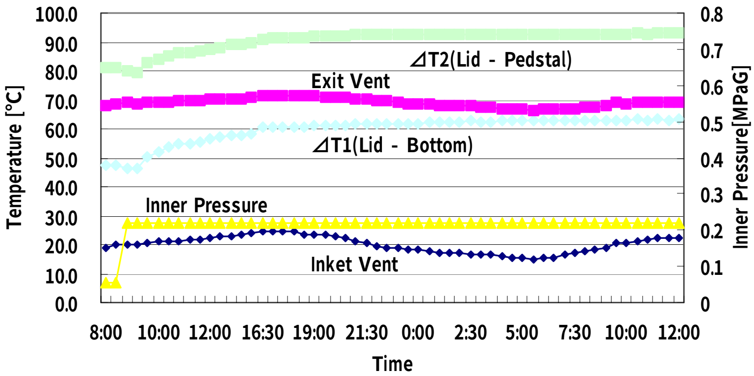


Fig.9(b) Temperature Response by Inner Pressure Change (from 0.056 to 0.22 MPaG)

(c) Daily Fluctuation

It may become difficult to detect the inner pressure change if the monitored temperatures change widely by the daily fluctuation of the environmental temperature (cooling air temperature from the inlet vent).

The daily fluctuations of the major temperatures and the environment are shown in Table 9. The fluctuation means temperature difference between maximum and minimum temperatures in a day. It shows that the environment fluctuations in the 3 cases vary because they mainly depend on the weather and season the experiments were performed. Table 9 shows that the temperature fluctuations of the environment are much smaller than the monitored temperature dT2(C2-P2) and the monitored temperatures are hardly affected by the daily fluctuations of the environment. The reason is that the concrete cask has large heat capacity and the measurement positions of the monitored temperatures are not exposed by the cooling air.

It is confirmed that daily fluctuation of temperatures hardly affect the monitoring value dT2 for the inner pressure change.

Table 9 Daily Fluctuation of Temperatures at the Major Points

	Position	Environment (Inlet Vent)	Canister		Pedestal	dT1 (C2-C1)	dT2 (C2-P2)
			Bottom	Lid			
	Mark	A1	C1	C2	P2		
Inner Pressure: 0.056MPaG	Average	18.4	111.6	155.2	77.8	43.5	77.3
	Fluctuation*	<u>3.5</u>	1.2	1.1	1.1	0.3	<u>0.7</u>
Inner Pressure: 0.218MPaG	Average	20.4	108.5	171.7	78.1	63.1	93.6
	Fluctuation*	<u>8.1</u>	1.4	1.3	0.7	0.6	<u>0.9</u>
Inner Pressure: 0.318MPaG	Average	20.7	105.5	174.0	76.0	68.4	97.9
	Fluctuation*	<u>6.9</u>	1.2	1.4	0.6	0.5	<u>1.1</u>

*: Fluctuation means difference between maximum and minimum temperature

(c) Heat Generation

The Helium circulation in the canister is also affected by the heat generation rate. The relation between the monitored temperatures dT2 and heat generation in the case of the inner pressure 0 MPaG is shown in Fig.10. It shows that the monitored temperature are almost proportional to the heat generation (solid line). The dot line shows the estimated temperature difference in the case of the inner pressure 0.3 MPaG based on the results of the heat generation 21 kW. The temperature change by the inner pressure change (from solid line to dot line) decreases gradually according to the heat generation decrease. But the temperature difference is estimated to be about 7 degrees Celsius even if the heat generation is 8 kW, which is estimated to equal to about 50 years cooling spent nuclear fuel. So it is thought that the temperature difference dT2 is detectable for the inner pressure change in low heat generation condition until the last period of the long-term storage.

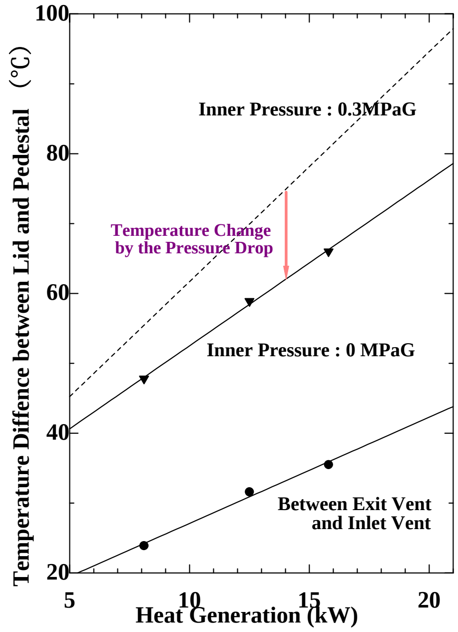


Fig.10 Relation between Heat Generation and Temperature Differnce

(3) Monitoring system

The conceptual design of the monitoring system is shown in Fig.11. The system consists of only 2 thermocouples and the accessories. Temperatures of the lid and pedestal are measured and the difference between them is monitored continuously within the system. Both thermocouples can be installed and replaced after the concrete cask is settled. It is thought that the advantages of the system are as follows;

- low cost : only 2 thermocouples
- easy maintenance : No active equipments (low possibilities of troubles)
- high reliability : low possibilities of misjudgement by using 2 measurements

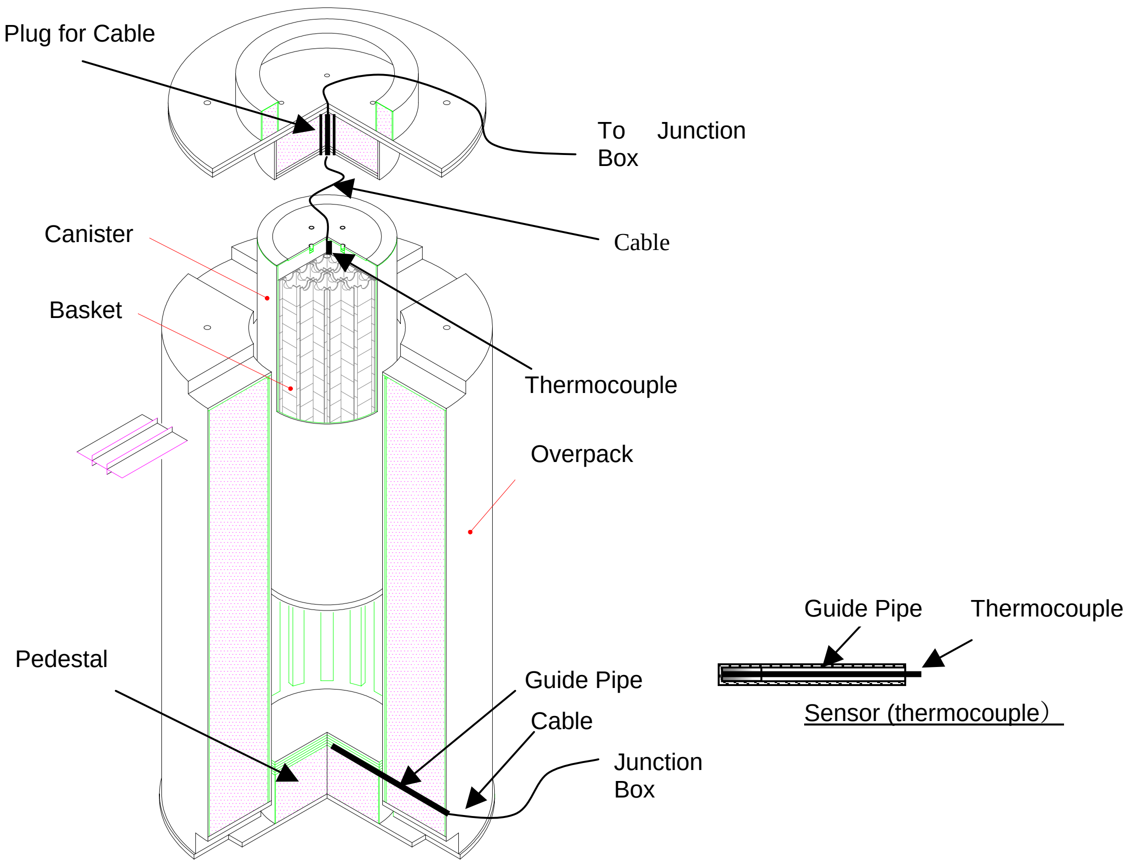


Fig.11 Basic Concept of the new Confinement Monitiring System

5. Conclusion

We manufactured a full-scale mock-up concrete cask and carried out thermal experiments under various conditions. All measured temperatures fall within acceptable limits and it is confirmed that the concrete cask has sufficient heat removal capability.
Benchmark analyses using a combined thermal calculation method were performed. Airflow rates and the temperature distributions outside the canister were calculated by using the finite volume computational fluid dynamics code FLUENT in the 1st step. The calculation results were used as the boundary conditions in the 2nd step and temperature distributions inside the canister were calculated by using the finite element ABAQUS code. Both calculated results agreed well with the measurements and the validity of the combined thermal calculation method was demonstrated by the benchmark analyses.
Furthermore we newly proposed a simple confinement monitoring system based on the relation between the canister inner pressure and the temperature difference between the canister lid and the pedestal. It was confirmed that the temperature difference changed about 20 degrees Celsius when the inner pressure dropped from results of the full-scale mock-up experiments. It is confirmed that it is large enough to compare with the effects of the daily fluctuation, the heat generation decreases and so on. And a conceptual design was investigated in consideration of the actual handling and maintenance. It is thought that the monitoring system is applicable for confirming confinement integrity.

References

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