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Demonstration Test Program for Long-term Dry Storage of PWR Spent Fuel

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Abstract

In Japan, the first interim spent fuel storage facility away-from-reactor (AFR) will start its operation for management of spent fuels until reprocessing. This facility stores BWR/PWR spent fuel assemblies using dry metal dual purpose casks (storage / transport) which will be transported to their destinations after the interim storage for decades. This facility is not equipped with a hot cell for opening the primary lid of the cask. Because one of the basic concepts of the facility is a simple operation not to handle a radioactive material directly, that reduces radiation exposure of workers and a risk of contamination troubles.

Although a visual inspection of spent fuel assemblies is usually carried out before spent fuel transportation, the visual inspection of spent fuel assembles is not carried out in the interim storage facility because the interim storage facility does not have a hot cell as noted above. Therefore, we are preparing for the demonstration test for long-term dry storage designed to confirm the spent fuel integrity during long-term dry storage by use of the test container which is able to reproduce storing the PWR spent fuel in the similar environment to actual casks.

In this presentation, we introduce the approach to store the PWR spent fuel for long-term and the status of the demonstration test with explanation of the outline of the demonstration test, the specification of the manufactured test container and the result of temperature evaluation of spent fuel assemblies during dry storage in the test container with a previously-verified assessment tool which is constructed to simulate the result of heat-transfer test for the test container.

Introduction

The first interim spent fuel storage facility in Japan, is preparing for maximum 50-year storage of spent fuels in dry metal casks for both transportation and storage. Spent fuels whose integrity was confirmed will be loaded and transported to the facility, and stored over the long term, maintaining its integrity based on research achievements in Japan and overseas. In addition, to reduce risk of exposure to workers and waste materials, the interim storage facility has no hot cell, and the spent fuels will be confirmed for their integrity indirectly by monitoring cask during storage and transported after the storage without opening the cask lid.

Currently, spent fuel storage in dry metal casks is a proven method mainly in Europe and the United States based on numerous tests including demonstration tests. In Japan, long-term integrity of PWR spent fuels is investigated and interim storage is planned under the conditions maintaining fuel integrity. On the other hand, Nuclear Regulation Authority (Formerly Nuclear Safety Commission of Japan) required the utilities to accumulate knowledge and experience on fuel integrity during dry storage, considering experience of spent fuel dry storage in Japan and the above facility features. Therefore, BWR fuels that are stored using dry casks in Fukushima Daiichi and Tokai Daini reactor sites have been confirmed several times for their integrity during storage.

Under the circumstances, the utilities plan a long-term storage test for fuel integrity in domestic research facility (Nuclear Development Corporation (hereinafter called NDC)) to accumulate knowledge and experience on long-term integrity of PWR spent fuel during dry storage.

Result

1. Demonstration Test Program

1.1. Test Overview and Process

Integrity of 48GWd/t type spent fuel and 55GWd/t type spent fuel are planned to be investigated in this demonstration test. The design of test container was already licensed and the test container was manufactured in fiscal 2013. Now the final licensing procedure for the test facility, NDC, is being performed. The demonstration test will start at the middle of 2017. For the first 10 years, only one 48GWd/t type fuel will be stored. Another 55GWd/t type fuel will be additionally loaded in fiscal 2027. The test is planned to continue for 60 years. In the demonstration test, it will be confirmed that appropriate test temperature, atmosphere in the container and no significant external force are maintained by monitoring temperature, visual appearance of the test container and lid sealing performance. It will be also confirmed that the spent fuel integrities are maintained by conducting internal gas sampling and Kr-85 analyses periodically. (Figure 1)

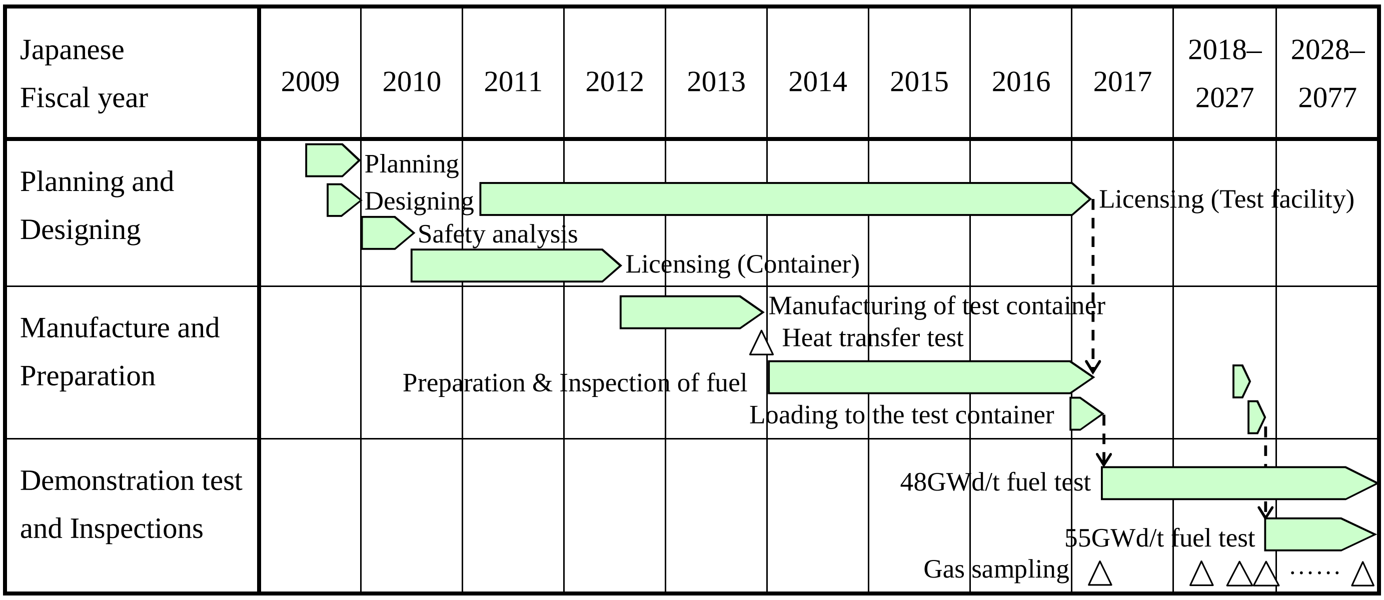


Figure 1 Time Schedule of Demonstration Test of PWR Spent Fuel Storage

1.2. Fuel Specification for Demonstration Test

The specifications of fuel for the demonstration test are shown in Table 1. In September 1993, one of 48GWd/t type fuels unloaded from Kansai Electric Takahama Unit 3 was transported to the hot laboratory in Tokai-mura (NDC). Post irradiated examinations (hereinafter called as PIE) of some fuel rods were conducted and now the fuel is being stored in the pool of the facility. 55GWd/t type fuel is only assumed and a proper spent fuel will be prepared for the test in the future.

Table 1 Fuel Specification for Demonstration Test

Fuels for Test	**48GWd/t Type Fuel**	**55GWd/t Type Fuel(assumption)**
Type	17×17	17×17
Burn-up (MWd/t)	42,800 (past record)	≤55,000
Cooling period (years)	Approx. 23 (as of June, 2017)	10 or more
Cladding material of fuel rods	Zircalloy–4	MDA or ZIRLO
Remarks	15 empty fuel rods*	Non

*Fuel rods used for PIE are not reinserted into the fuel assembly.

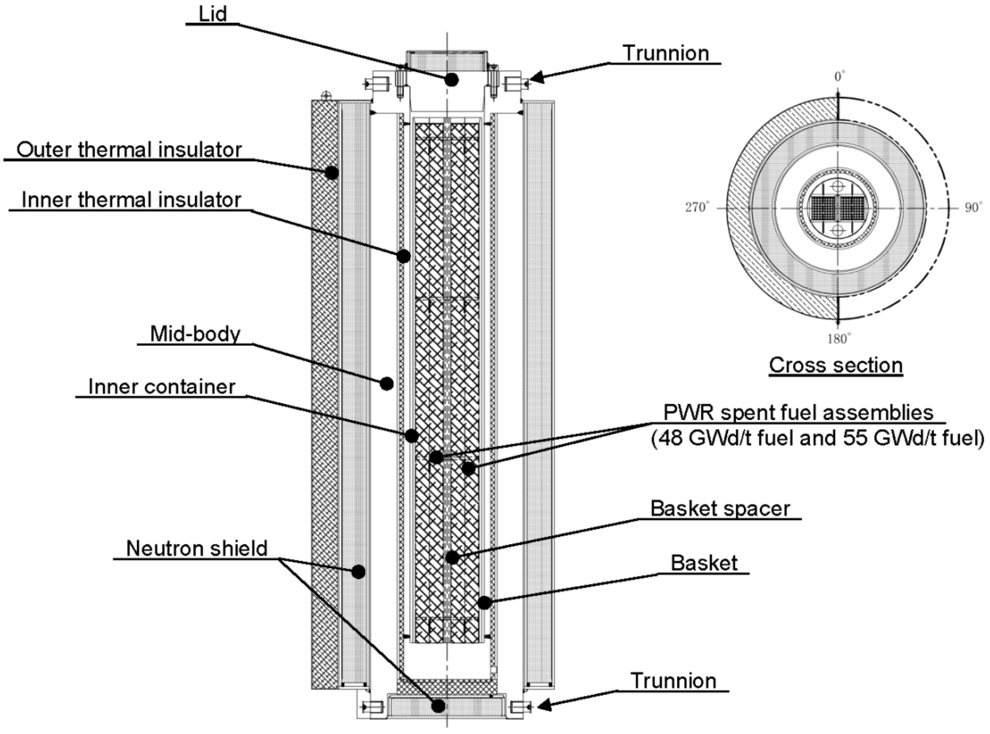
1.3. Outline of Container

To meet the test purpose, the test container is designed to store two of Type 17×17 PWR spent fuels for 60 years. Also, it is designed to be able to simulate temperatures, pressures and atmosphere of an actual metal cask. Furthermore, maintenance of sealing, subcriticality and shielding performance are required to implement the test safely. The outline of the test container is shown in Figure 2.

A basket spacer (part of a basket) is made of boron containing aluminium alloy to maintain subcriticality. A container body mainly consists of an inner cylinder as a containment boundary, a thick mid-body for gamma-ray shielding and resin for neutron shielding. A thermal insulator is placed between the inner cylinder and the mid-body as a temperature control component simulating actual cask temperature, since a design heat load of two fuels stored in the test container is much lower than the assumed heat load of an actual cask. For the first 10 years, only one 48GWd/t type fuel will be stored with lower heat load, so that another insulator is placed outside of the container to adjust its initial temperature.

The container has a single lid with double metal gaskets. A performance of containment boundary at lid will be monitored by monitoring pressure between the gaskets.

The height of the test container is approx. 5.2m and its outer diameter is approx. 2.1m.



(a) Only 48GWd/t fuel installed (b) 48&55GWd/t fuels installed

Figure 2 The Outline of the test container

1.4. Verification Method of Fuel Integrity

Figure 3 shows a flow diagram of the demonstration test. The following inspections to confirm integrity of fuels stored are conducted before, at the beginning of, and during the demonstration test.

1.4.1. Confirmation before Demonstration Test

The spent fuel assembly used for the demonstration test is inspected visually in the pool of the facility before the demonstration test. The integrity of the 48GWd/t type fuel was confirmed by observing visual appearance of 4 outermost surfaces of the fuel assembly with an underwater camera.

1.4.2. Confirmation at Beginning of Demonstration Test

After a loading operation of 48GWd/t type fuel into the test container and also after an additional loading operation of 55GWd/t fuel, it is confirmed that there is no leak of the fuel rods by conducting gas sampling and analyses of Kr-85 and compositions.

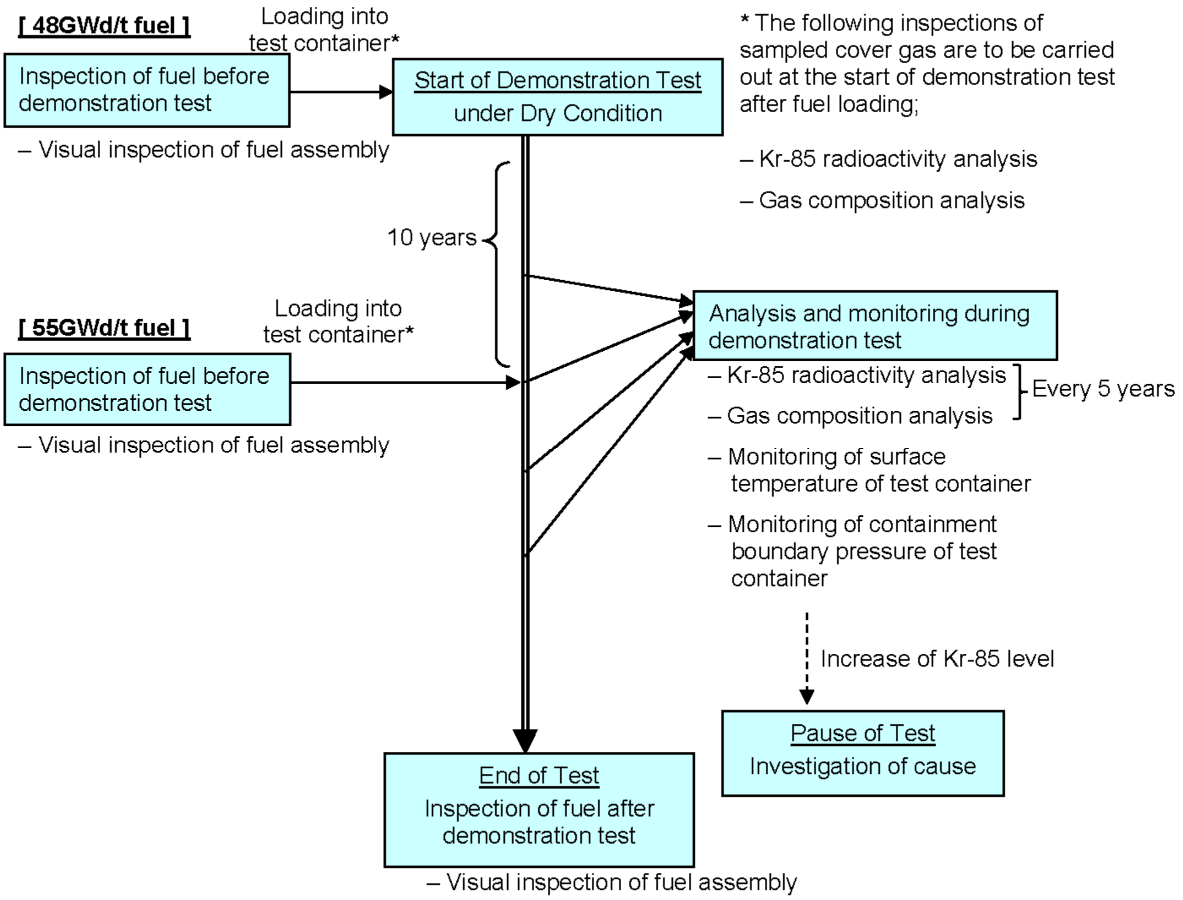


Figure 3 Flow Diagram of Test Programme

1.4.3. Confirmation during Demonstration Test

The initial test conditions are confirmed to be maintained by periodical sampling and analyses of gas from inside of the test container and monitoring of its temperature and pressure from outside during storage until the completion of the test.

1.4.3.1. Gas Sampling

For the purpose of detecting fuel rod failure, gas samples inside of the test container are taken to conduct gas analyses periodically every 5 years. The gas sampling is conducted by connecting the previously-evacuated sampling pod to the lid port leading to inside of the test container through a valve(Figure 4). The sampled gas is analyzed for radioactive gas (detection of Kr-85) with a Ge semiconductor detector and components with a mass spectrometer. If any problems like significant increase of Kr-85 level are detected, the test will be paused to evaluate effect on safety and investigate the cause. When examination of fuel integrity shows a possibility of fuel failure, the fuel might be investigated in detail.

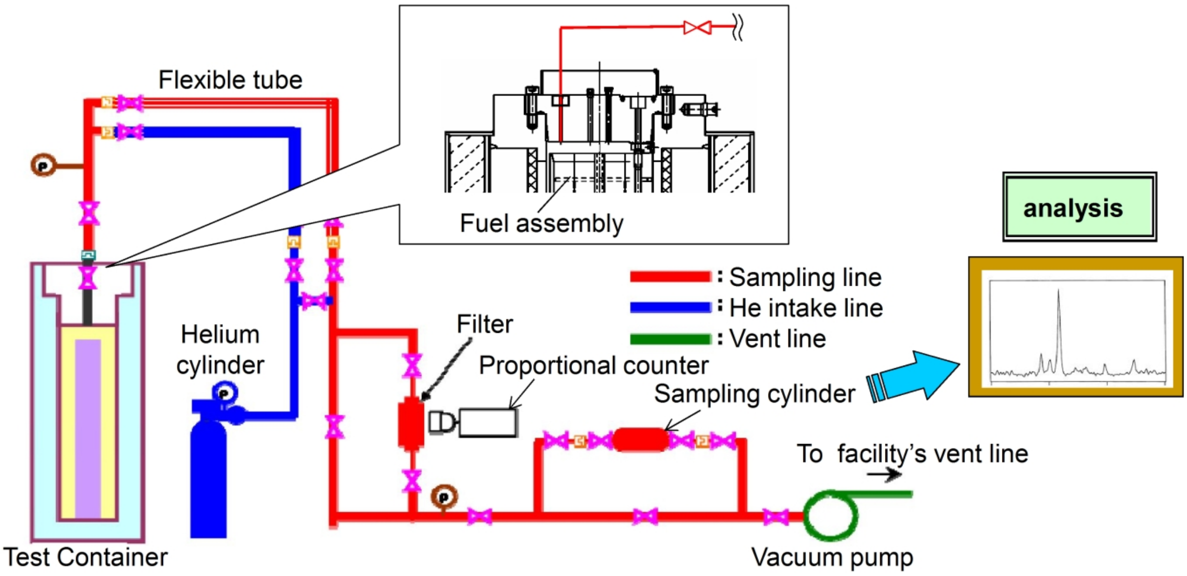


Figure 4 Outline Drawing of Gas Sampling

1.4.3.2. Monitoring of Containment

Monitoring of the following items is performed determining its frequency during the test.

1.4.3.2.1. Temperature monitoring

With the aim of estimating temperature history of spent fuels, thermocouples are installed on the outer surface in the middle area of the test container to monitor temperature. Temperature of spent fuels is estimated based on the outer surface temperature and external temperature by using a previously-verified assessment method for temperature of the test container and fuel assemblies.

1.4.3.2.2. Confirmation of integrity of the test container

To confirm containment integrity of the test container, pressure monitoring is performed using pressure gauges installed to a buffer tank leading to gap between double metal gaskets, where is pressurized with helium gas(Figure 5). Gas temperature is also measured. Also, to confirm that there is no problem on the test container, visual inspections of surface of the test container and its fixing conditions are conducted.

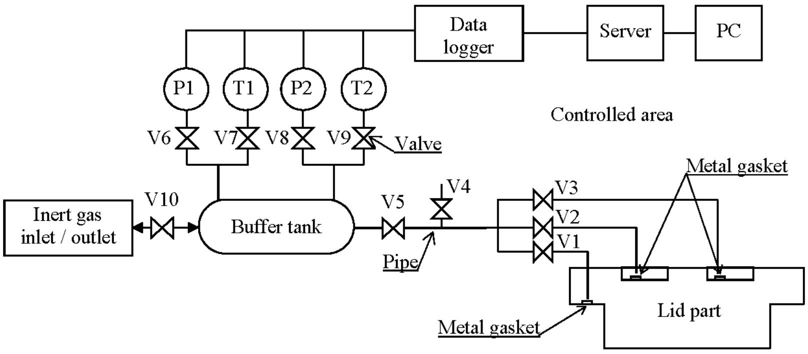


Figure 5 Schematic Drawing of Pressure Monitoring

1.4.3.2.3. Inspection of measuring equipment

Thermocouples, temperature indicators, pressure gauges, etc. are calibrated or replaced with calibrated equipment to provide quality control of measuring equipment.

2. Test Container

2.1. Designing of Test Container

2.1.1. Current Knowledge and Experience

Spent fuel assemblies after confirming their integrity are stored in metal casks with inert atmosphere. Thermal degradation, chemical degradation, etc. are assumed as factors affecting fuel integrity during storage. However, spent fuel integrity can be maintained if the fuel assemblies are stored maintaining inert atmosphere in cask cavity under appropriate temperature conditions without physical impact during handling. Spent fuel during storage without any physical impact can be evaluated as no damage on their integrity to thermal, chemical, radiation and mechanical degradation as shown in Table 2.

Integrity of spent fuel after storage can be confirmed by checking cask temperature, sealing performance and external force conditions during storage and cask handling.

In the United States, spent fuel dry storage test is being carried out in Idaho National Laboratory (INL) using CASTOR cask. PWR spent fuel assemblies brought from Surry Nuclear Power Plant, (15×15, of BU up to approx. 35,700MWd/t, 2~4 years as cooling period before storage), were inspected when the above mentioned storage test period became approx. 15 years. As a result of radioactivity analysis of gas inside of the container, no Kr-85 or damage of fuel cladding tubes was detected. Furthermore, creep tests of fuel cladding tubes, confirmation of hydride reorientation, measurement of irradiation hardening, observation of cross-sections, etc. ensure no damage or significant change in the cladding tubes due to aging degradation during storage. (Ref. [1], [2])

Table 2 Evaluation of Degradation Events

Conditions to be considered	**Technical Evidence**	**Actual Condition of Stored Cask**	**Test Conditions (target)**
Thermal degradation	No embitterment due to hydride reorientation, failure due to creep strain, recovery of irradiation hardening, or stress corrosion crack under 100MPa or less circumferential stress at 275°C. (Ref. [3])	Around 200°C※ (Gradually decrease with decrease in decay heat)	Around 220°C (Gradually decrease with decrease in decay heat)
Chemical degradation	Negligible oxidation/hydrogen absorption during storage (inert gas atmosphere) compared to that during in-core irradiation	He gas atmosphere Moisture: 10% or less	He gas atmosphere Moisture: 10% or less
Radiation degradation	Negligible neutron irradiation influence during storage Saturation of mechanical strength due to neutron irradiation at relatively low burn-up (around 5GWd/t)	Burn-up of stored fuel: Maximum 47GWd/t	Burn-up of contained fuel: 5GWd/t or more
Mechanical degradation	Maintenance of integrity under normal test conditions of transport(free drop) (Acceleration:20 to 45G)	During storage: static position During earthquakes: Acceleration of 1G	During storage: static position During earthquakes: Acceleration of 1G

※Design heat load including a safety margin of 5% and an ambient temperature of 10 ˚C are taken into account

2.1.2. Simulated Environment of Actual casks

Simulated environment of actual casks is discussed considering technical knowledge and experience under three conditions (thermal, chemical, and radiation degradation) and interim storage condition assumed for spent fuel under normal storage condition with actual casks.

2.1.2.1. Temperature

2.1.2.1.1. Target value of fuel maximum temperature

The maximum temperature of fuel cladding tubes during the storage test is set around the design value of actual casks since it is desirable to simulate temperature environment of actual casks. Limit temperature having no effect on fuel integrity during storage is respectively set as 275°C and 250°C for 48GWd/t fuel and 55GWd/t fuel. (Ref. [3], [4]) Fuel temperature during tests is estimated based on the outer surface temperature and external temperature by using a previously-verified assessment method for temperature of the test container and fuel assemblies.

2.1.2.1.2. Thermal design of container

The test container has a thermal structure of removing heat by natural cooling without external power as with actual casks to simulate gradual temperature decrease easily in the test container and to avoid power supply troubles. Thermal design of the test container is the most important to simulate fuel temperature of actual casks. Therefore, its heat-transfer performance is verified by a heat-transfer test with a heater simulating actual fuel condition as well as FEM analyses for its designing. See the section 2.3 for the result of the heat-transfer test.

Since decay heat at additional loading of 55GWd/t fuel is relatively high (approx. 1.4kW), temperature is controlled with only the thermal insulator inside of the container.
Under the condition loading only 48GWd/t fuel for the first 10 years, another insulator is placed outside of the container and low-pressure helium gas is applied as internal gas since the decay heat is extremely low and simulation of actual casks internal temperature is difficult. This is intended to control thermal conduction of the gas and obtain large temperature difference inside of the test container as with the vacuum condition by setting internal gas as low pressure. The low pressure setting of internal gas, which causes no significant change in internal atmosphere, would not affect the simulation performance of chemical/thermal effect of actual casks on surface corrosion and temperature distribution.
Fuel temperature in the storage test is approx. 220℃ for 48GWd/t fuel and approx. 190℃ for 55GWd/t fuel at the beginning of the test. As mentioned above, both 48GWd/t fuel and 55GWd/t fuel approximately meet the target value of the fuel temperature. Temperature decrease in 48GWd/t fuel at loading of 55GWd/t fuel is within 20°C.

2.1.2.2. Test atmosphere

To meet the purpose of the long-term storage test, atmosphere in a test container around a fuel assembly must be specified. First, the test container is filled with inert gas (helium gas) having negative pressure as with actual metal cask cavity. Then, vacuum drying operation in the same procedure as actual casks is carried out at loading a fuel assembly before backfilling of inert gas. At the completion of the operation, amount of moisture inside the test container is confirmed to be as low as enough. Although internal surface area including the container inside and fuel assemblies is different from actual casks, residual moisture has little effect on aging degradation of spent fuel in terms of corrosion of cladding tubes and hydrogen absorption.

Maintenance of inert atmosphere in the test container is confirmed during tests by monitoring pressure at lid containment boundary to confirm maintenance of sealing performance.

2.1.2.3. Irradiation

Due to effect of neutron irradiation on mechanical properties of cladding tubes, mechanical strength shows saturation and ductility shows slow deterioration at low burn-up with relatively low dose around 5GWd/t. Burn-up of fuel assemblies used for the storage test is 42.8GWd/t and in-core neutron fluence is 1021 to 1022n/cm2. The mechanical properties of cladding tubes are located in this region. On the other hand, neutron fluence during storage is lower than 1016n/cm2 for actual casks and one digit smaller in the storage test. However, neutron fluence in the storage of actual casks and the storage test is extremely small compared to in-core irradiation and they are equal in terms of effect on mechanical properties of cladding tubes.

2.1.3. Safety Analyses of Test Container

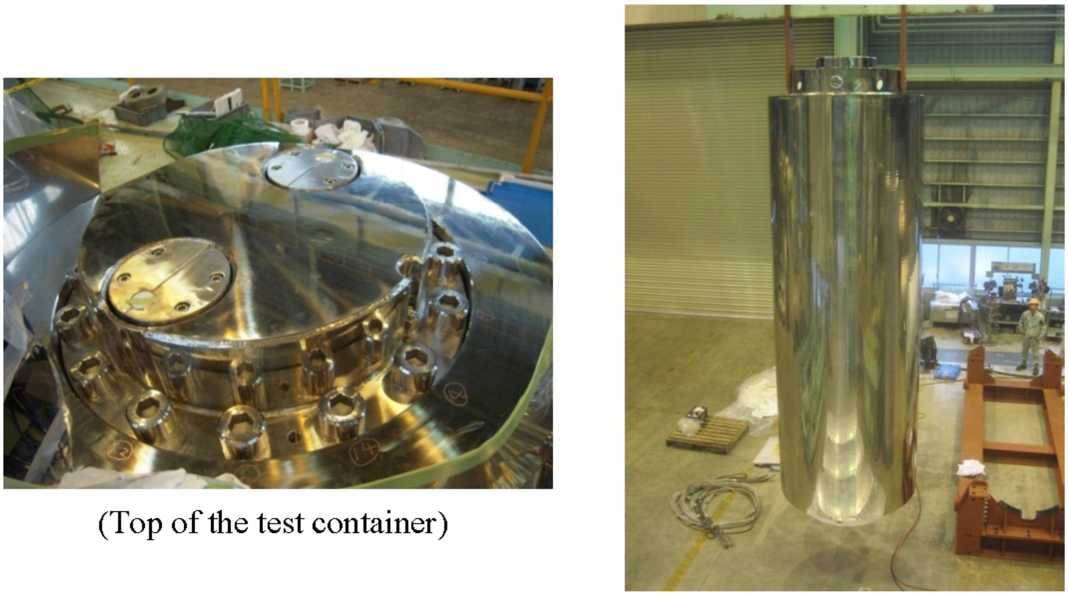
Safety analysis of the test container, shielding, subcriticality, containment, heat transfer and structure, was conducted. Thermal stress, handling and some accident are considered in structural analyses of the test container. Major results of safety analyses are shown in Table 3.

2.2. Manufacturing of Test Container

The test container used for the demonstration test was manufactured from fiscal 2012 to 2013. The photos of the test container are shown in Figure 6. The material list and the main specification of the component of the test container are shown in Table 4.

Table 3 Major Result of Safety Analyses of Test Container

Analysis	Calculating		Result	Criteria
Shielding	Maximum expected dose rates	Lateral saide	24.9µSv/h	≤25µSv/h
		Top side	144µSv/h	≤250µSv/h
Criticality	Effective multiplication constant		0.92	≤0.95
containment	Nuclide release rates keeping vacuum during the storage test		1.0×10^{-9}Pa･m^3/s	≤4.4×10^{-7}Pa･m^3/s
Heat Transfer	Temperature of fuel and container	48GWd/t fuel	240°C	≤275°C
		55GWd/t fuel	250°C	≤250°C
		Container surface	70°C	≤85°C
Structure	Stress	Handling	347MPa	≤394MPa(Sy)
		Abnormal loading	186MPa	≤578Mpa(Sy)
		Seismic	167Mpa	≤687Mpa



(Top of the test container)

(Full view of the test container)

Figure 6 Test Container (Photos)

Table 4 Material List of the Component of the Test Container

Component	Material	Standard
Inner container/Flange /Bottom Plate	Stainless Steel	JIS G 3214 SUSF304L
Mid-body	Carbon Steel	ASTM A350M LF5 Class1
Outer Shell	Stainless Steel	JIS G 4304 or JIS G 4305 SUS304
Trunnion	Stainless Steel	JIS G 4303 SUS630-H1150
Inner Thermal Insulator	Ceramic Fiber	-
Neutron Shield	Resin	-
Basket	Stainless Steel	JIS G 4304 or JIS G 4305 SUS304
Basket Spacer	Boron Contained Aluminium	-
Lid	Stainless Steel	JIS G 3214 SUSF304

2.3. Heat Transfer Test

To evaluate a thermal performance of the test container, heat-transfer tests were carried out using the test container. Outline of the heat-transfer tests is shown in Figure 7. Two mock-ups of fuel with heaters which simulate the decay heat of spent fuel assemblies were stored into the test container. Temperature of each component of the test container was measured during the heat-transfer test.

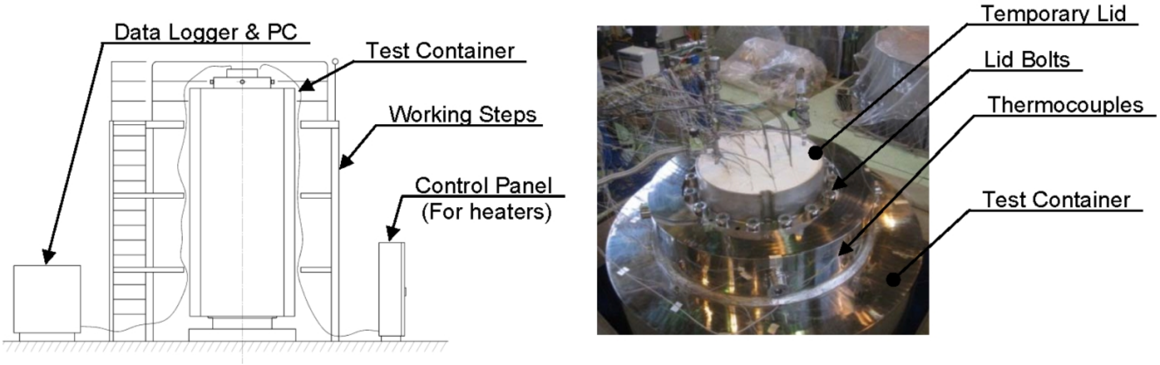


Figure 7 Outline of Heat-Transfer Test

Two heat-transfer tests were conducted. Test conditions of each test are shown in Table 5. In the first heat-transfer test (case 1), only one of the mock-ups of fuel which simulate the decay heat of the 48GWd/t type fuel was heated under the vacuum condition in the cavity. In the second test (case 2), both mock-ups of fuel were heated under the condition with helium gas in the cavity. Temperatures at each point when the mock-ups of fuel reached to the maximum temperature are listed in Table 6.

Table 5 Test Conditions of Heat-Transfer Tests

Test Case	**Case 1: One Heater (Simulated 48GWd/t fuel)**	**Case 2: Two Heaters (Simulated 48 and 55GWd/t fuels)**
Heat Load	513W (513W / -)	1397W(428W / 969W)
Filling Gas into the Cavity	Vacuum	Helium Gas
Outer Thermal Insulator	Attached	Detached

Table 6 Temperatures of Each Component when Mock-up of Fuel Reached to Maximum Temperature

Component	**Case 1: One Heater**	**Case 2: Two Heaters**
Outer Shell	513W (513W / -)	1397W(428W / 969W)
Outer Shell	22.5˚C	18.5˚C
Inner Body	79.7˚C	158.4˚C
Basket	137.1˚C	171.1˚C
Mock-up of 48GWd/t fuel	206.2˚C	186.5˚C
Mock-up of 55GWd/t fuel	-	192.4˚C
Lid (Inner Surface)	24.3˚C	53.0˚C
Bottom Plate (Inner / Outer Surface)	74.9˚C/ 15.9˚C	133.9˚C/ 22.3˚C
Ambient Temperature	9.2˚C	10.8˚C

3. Preparation for Demonstration Test

3.1. Thermal Analysis

3.1.1. Simulation Analysis for the Heat-Transfer Test

Thermal analysis was carried out for the purpose of the simulation of the heat-transfer test to estimate the temperature of spent fuels in the demonstration test. The simulation analysis for case 1 was conducted by using ABAQUS code and the simulation analysis for case 2 was conducted by using FLUENT code in order to consider a convection of Helium gas in the cavity.

Temperature distributions of the test container in case 1 and case 2 are shown in Figure 8 and Figure 9 respectively. Comparing the analysis results with the heat-transfer test results, the temperatures of the simulation analysis are well agreed with the heat-transfer test results as shown in Table 7, so that the temperature evaluation method was verified.

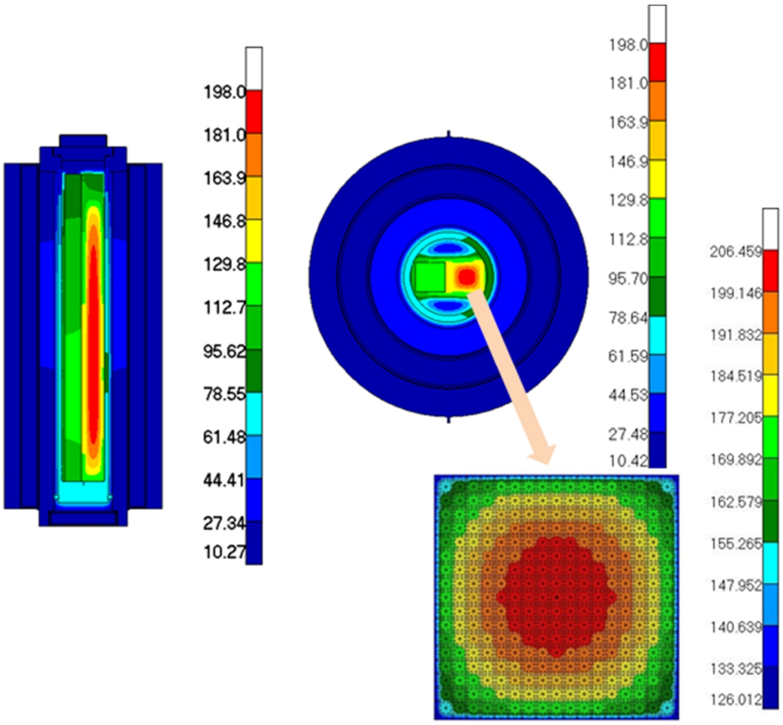


Figure 8 Temperature Distribution at the Maximum Temperature of Heater (Case 1)

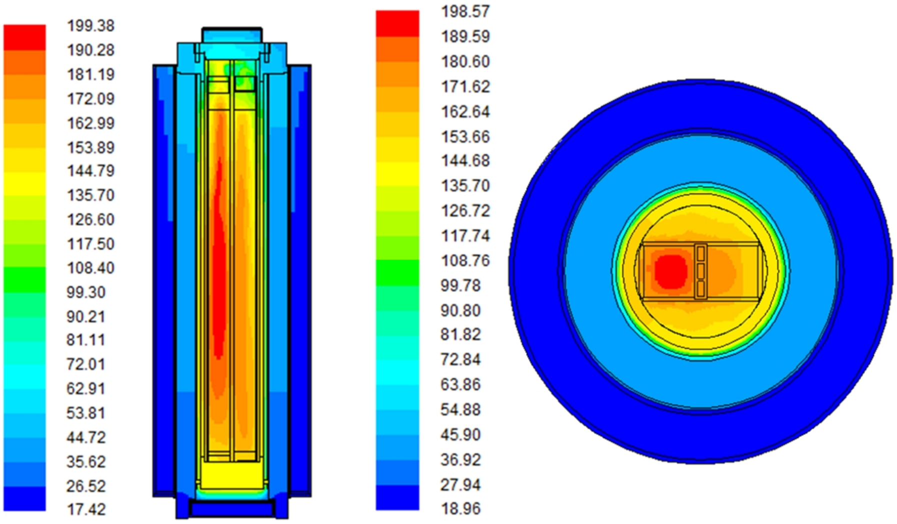


Figure 9 Temperature Distribution at the Maximum Temperature of Heater (Case 2)

Table 7 Comparison of Temperature between
Heat-Transfer Test and Simulation Analysis

Component	Case 1: One Heater		Case 2: Two Heaters	
	Test	Analysis	Test	Analysis
Outer Shell (Outer Surface)	22.5˚C	25.6˚C	18.5˚C	19.0˚C
Mock-up of 48GWd/t fuel	206.2˚C	205.9˚C	186.5˚C	179.8˚C
Mock-up of 55GWd/t fuel	-	-	192.4˚C	198.6˚C

3.1.2. Evaluation of Temperature during Demonstration Test

Initial temperature of the fuels at the installation into the test container was evaluated by using the verified method mentioned above. The evaluated fuel temperatures are shown in Table 8. As shown in Table 8, evaluated fuel temperatures are almost satisfied the target temperature which is set according to the results of thermal analysis in the report of PWR cask[2] so that the test container has satisfying thermal performance for simulating actual cask temperature.

Table 8 Temperatures of Each Component when Mock-up of Fuel Reached to Maximum Temperature

Case		Evaluated Temperature	Target Temperature*
One Fuel loaded	48 GWd/t fuel	214˚C	200˚C
Two Fuels loaded	48 GWd/t fuel	170˚C	-
	55 GWd/t fuel	188˚C	200˚C

* Design heat load including a safety margin of 5% and an ambient temperature of 10 ˚C are taken into account.

3.2. Fuel Inspection

Before loading 48 GWd/t type fuel into the test container, visual inspections of each outer surface of the fuel assembly through its length were carried out as shown in Figure 10. It was confirmed that the fuel has no significant crack (hair-line crack, harmful scratch etc), no deformation and no adhesion of foreign substances. 4 fuel rods were extracted from the fuel assembly and the visual inspections, the dimensional inspections and the oxide film thickness measurement for these fuel rods were carried out. After that these fuel rods were inserted into the fuel assembly again. These inspection results could be helpful in case that any problems like a leakage of fuel rod were occurred.

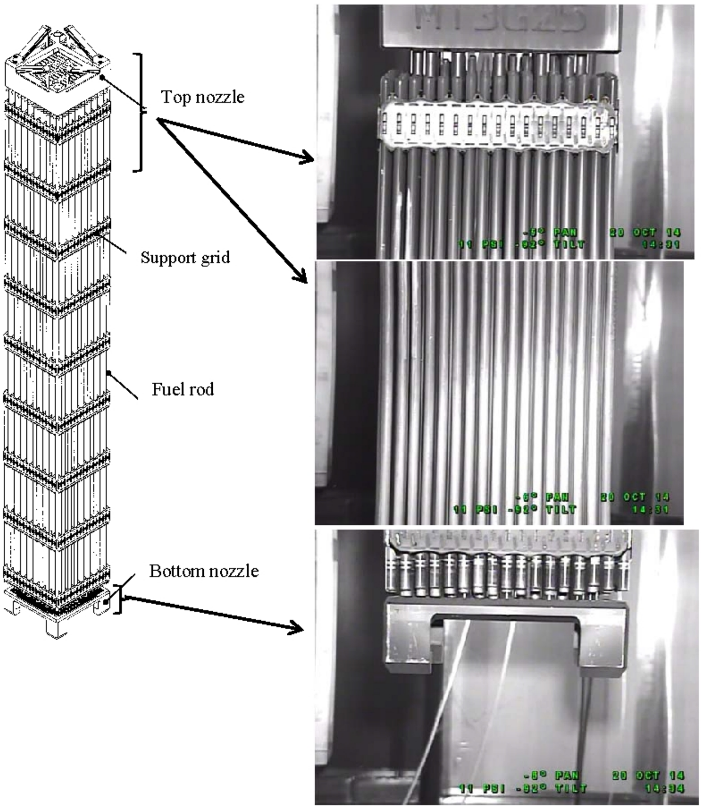


Figure 10 External Surface of 48GWd/t Type Fuel

Conclusions

Some Japanese utilities are planning to conduct the demonstration test for up to 60 years to accumulate knowledge and experience on long-term integrity of PWR spent fuel during dry storage.

The design of the container was licensed and the test container was manufactured from fiscal 2012 to 2013. Thermal design of the test container is important in order to simulate temperature of an actual cask. To evaluate a thermal performance of the test container, heat-transfer tests were carried out using the test container.

Fuel temperatures at the installation into the test container were evaluated based on the heat-transfer test results, and it was confirmed that the container has satisfying thermal performance for simulating actual cask temperature. Moreover, the visual inspections for 48GWd/t type fuel have been carried out before loading and its integrity was confirmed.

Now final licensing procedure for the test facility is being performed, and then the demonstration test of 48GWd/t fuel will start at the middle of 2017.

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