The storage container for demonstrate BWR spent nuclear fuel dry storage in Taiwan

Y J Lin1, C H Chen1, 2, C W Yang1 and C H Chen1

1Institute of Nuclear Energy Research, 1000 Wenhua Rd. Jiaan Village, Longtan District, Taoyuan City 32546, Taiwan
2Department of Bioenvironmental Systems Engineering, National Taiwan University, No. 1, Sec. 4, Roosevelt Rd., Taipei 10617, Taiwan
*Email: chrislin@iner.gov.tw

Abstract. Considering the unique operation of each nuclear power plant and lack of BWR fuel examination data after dry storage, the Taiwan Power Company and Institute of Nuclear Energy Research conduct the “The Nuclear Fuel Storage Demonstration Project in Taiwan” to collect the data of the fuel characteristics under dry storage. In this project, BWR fuel rods among different fuel designs and fuel vendors will be loaded into a simulated storage cask for 10 years. Different temperatures and environments will be adopted, for simulated normal storage condition and acceleration experiments be performed. Non-destructed examinations will be executed prior to loading the fuel rods and periodically during storage. After 10 years, the fuel rods will be extracted and examined non-destructively and destructively. This paper summarized the methodology to demonstrate the adequacy of spent fuel dry storage, the design and fabrication of the simulated storage containers, the results of performance test and the project progress. Two containers will be used in the prospective experiments; one is for the normal storage condition. The other is for accelerated experiments and various storage conditions. After completion of this project, the collected data and research results will be compared with other international projects to provide the technical basis in Taiwan.

1. Introduction

1.1. Background
There are total four Boiling water reactor (BWR) units and two Pressurized water reactor (PWR) units in Taiwan, which are two BWR units in Chinshan nuclear power plant, two BWR units in Kuosheng nuclear power plant and two PWR units in Maanshan nuclear power plant. The national used nuclear fuel management strategy is three steps: pool storage on site, dry storage on site and final disposal. The operation licenses of the two units in Chinshan nuclear power plant has been expired in December 2018 and July 2019. According to the used nuclear fuel management strategy in Taiwan and dismantled plan of Chinshan nuclear power plant, the used nuclear fuel should be moved from spent fuel pool to the dry storage in order to execute the dismantled activities. All the used nuclear fuel after confirming their integrity will be loaded into the dry storage systems, transported to the storage facility, and stored over the expected time frame to maintain its integrity before moved to the final disposal repository. Currently, there have been several tests and demonstration projects around the world, including the High Burnup Data project in USA and PWR Demonstration Test Program in Japan. However, there are only few data on BWR fuel in dry storage. In order to respond the public concern on spent fuel safety and take the specific operating conditions of the plant into account, Taiwan Power Company and Institute
of Nuclear Energy Research (INER) work together to conduct the “The Nuclear Fuel Storage Demonstration Project in Taiwan” to collect the local fuel characteristics data under dry storage. INER owns the only hot laboratory in the country and has the ability and experiences to test and analyze with irradiated nuclear fuels and high radioactive nuclear power plant components. It helps the nuclear power plant in safety operation and provided suggestions on the issues related to the long-term storage and final disposal of spent nuclear fuel.

1.2. Project scope
There will be around 18,000 discharged BWR fuel assemblies from Chinshan nuclear power plant and Kuosheng nuclear power plant after 40 years operation. Since it is hard to inspect and confirm the fuel status after loading to the dry storage cask, it is important to have a demonstration cask with local used nuclear fuel rods. Even though the dry storage projects in Taiwan for both Chinshan and Kuosheng nuclear power plant are waiting for the local government approval to load the fuel assemblies, Taipower and INER decided to load the used nuclear fuel rods from both two BWR nuclear power plants to a demonstration cask and an acceleration cask inside INER’s hot cell. There is no need to apply for the license of both casks since they are put inside the hot cell, which can save the cost and time.

In this project, the following activities are performed through the initial period. Here are activities related to Storage Container:
- Developing the bolted lid storage casks with the functions of adjustable inner gas composition and temperature.
- Loading the spent fuel rods into the bolted lid demonstration cask and storing the cask inside the hot cell.
- Monitoring and performing periodic NDE of the stored rods during the storage timeframe.

After 10 years storage, the anticipated activities to complete the project would include:
- Opening the cask inside the hot cell.
- Extracting fuel rods for subsequent examination.
- Performing the non-destructive and destructive examinations of the stored rods.

In order to respond to the public concern and regulatory enquiry, another cask named “acceleration cask” is also prepared to address the issues related to the spent fuel behavior under different situation. The test plan for the acceleration cask is under discussion between Taipower, INER and the regulatory.

2. Research methods

2.1. Design consideration and functional requirement
This research focus on the design and manufacture of storage containers, and placed storage containers in the laboratory in Taiwan that can only execute inspections of high-level radioactive substance. In order to obtain the experiments data, we adjust the environment of storage container to compare the change of used nuclear fuels in different condition.

The storage container placed in the hot cell is 6 m in length, 3 m in width and 4.5 m in height. The detail Schematic of the hot cell is shown in Figure 1. Any transport of equipment and parts of the storage container into the hot cell must rely on the transfer port through cranes and the manipulator. The crane in the hot cell have the capability of lifting 1 metric ton weight. The operation of the storage container must be controlled by the manipulator with the capability of loading 15 kg as maximum.

Because the thickness for shielding of the hot cell is 1 m, the operator can only observe inside the hot cell through a peep window which has a blind spot about 1 m on the left and right sides of the peep window. The schematic of peep window is shown in Figure 2. If there are any parts need to be replaced, operator need to control the manipulator for this replacement through the peeping window.

To overcome the limitation of the environment of the hot cell, ASTM A240 Type 304 was chosen to manufacture the storage container mainly. The storage container is designed in a long cylindrical shape in a diameter ratio of 19.4 to enable the storage container to be sent into the hot cell through the transfer ports with inner diameter of 250 mm on both sides of the hot cell. The 6-inch inner pipe is with an outer diameter of the 165.2 mm and a thickness of 2.8 mm. Space in the pipe can be applied to store used
nuclear fuel, and then fill helium and heat the space. The pressure in the pipe during the period of storing used nuclear fuel is higher than 1 atmosphere and the temperature will reach up to 500 °C. The diameter of the outer pipe is 216.3 mm, and the thickness of the outer pipe is 6.5 mm. The inner and the outer pipe are in adiabatic condition by a vacuum layer.

2.2. Regulations and standards
According to ASTM material specification, yield strength of A240 Type 304 is 30 ksi equal to 206.9 MPa, and the ultimate tensile strength is 75 ksi equal to 517.2 MPa [1].
The outer pipe shall pass the vacuum leak test in accordance with the requirements of NUREG-1536 [2]. The test pressure conducted for the inner pipe shall pass in accordance with the requirements of section 11.6.3 [3] of CNS 9801 "Pressure and leak for pressure vessels" and keep it at least 10 minutes. The criteria is that there is no any leak on the weld bead at any position of the container.
The thickness of the storage container of the pressure-bearing part shall in accordance with the requirements of Article 12, Section 2, Chapter 2 of the “Standard of Safety Inspection for Pressure Vessel”[4] and shall be 2.5 mm or more than. The thickness of seamless 6-inch inner and the 8-inch outer 304 stainless steel pipe which schedule is SCH-5 equal to 2.8 mm meets the safety inspection standards.
After the completion of the welding of the storage container, the surface of the weld bead must be inspected in accordance with CNS 12661 “Method of Test for Liquid Penetrant and Classification of Indication”[5]. All visible weld covered on the shell of storage container needs to execute visual test in accordance with CNS 13021 "Method of visual test for the welds of steel structure"[6] and the qualification should meet the national standard CNS 9788 "Pressure vessels (General standard)”[7] or equal.

2.3. Design and constitution of system (equipment)
The storage container will be set in the hot cell for a long time. For the consideration of radioactive contamination, mechanical properties, corrosion resistance and low outgassing in operation and maintenance, all components of storage container are made of 304 stainless steel. Here are advantages of choosing 304 stainless steel as material as below [1]:

• The mechanical strength for withstanding the external force generated by the pressure difference is satisfactory.
• Low outgassing rate and low permeability.
• Chemical stability to resist the oxidation and corrosion.
• Nice ability to endure extremely high and low temperatures.

Due to the limited space of the hot cell, it is difficult to do any process in this limited space. Therefore, the operation and maintenance in an easy way shall be considered in the design of the storage container. Here are features of the storage container as below:

• Heating layer in inner pipe: The temperature control system provides an environment full of helium in different temperatures to simulate the environment of 100% helium surrounded the used nuclear fuel or the accelerated corrosion test in an environment full of mixed gas (80% He+20% O₂) at high temperature to observe the long-term stability and the changes of the used
nuclear fuel. Additionally, the system also help to obtain the physical and chemical data of the fuel regularly.

- Vacuum insulated layer: Preserve the heat in the storage container effectively instead of rapid loss. The inner pipe is heated and the outer pipe is vacuum insulated. This design reduce the cost of heating and long-term operating effectively.

- Quick coupling at level of nuclear energy: Use quick coupling which part number is RBE 03.1150/IC/TM designed by STAUBLI corporation for helium sampling, filling helium and vacuum pumping between 6-inch inner pipe and 8-inch outer pipe. By this component, it is easy for manipulator to remove and install the quick coupling as shown in Figure 3. As a result, it can provide guarantee of safety in design and all the features to reduce the difficulty of operating in the radiation environment.

- Stainless steel ball valve: To meet the airtight requirements for used nuclear fuel in storage space, we choose 1/2 inch metal seated ball valve which item number is 305M designed by ZIPSON Valve Corporation. Detail of the ball valve is shown in Figure 4. For sending used nuclear fuel to the storage container easily, we changed the design of ball valve by cutting the flange end at one side, and then the bell mouth is welded. On the other hand, the design of the hole which is in a socket at the other side is convenient for aligning fuel with perforated pipe.

- Stainless steel perforated pipe: Drawing of perforated pipe are as shown in Figure 5. Nuclear fuel rods can be horizontally set in the perforated pipe with supporting plates. The perforated pipe distribute the transfer heat evenly. To avoid the serious friction between the fuel rod and the rough surface of perforated pipe, rough surface of perforated pipe face outward. The porous type of design can improve heat transfer efficiency and help to provide suitable storage environment and temperature.

- Supporting plate: Supporting plate can support perforated pipe to contain fuel rods and strengthen the structure of the storage container effectively by combining it to perforated pipes. There are three supporting plates are added to prevent displacement of perforated pipe.

- Nuclear fuel rods: The length of the nuclear fuel rods loaded in storage container is set to 4,150 mm. The full length of the cavity of the heating layer in inner pipe is 4,174 mm. It is estimated maximum length of the fuel rods in the experiment is 4,138.5 mm. All mentioned as above can be covered by designed storage container.

- Electric heat pipe and temperature measuring rod: This two components are connected with the storage container by a quick coupling for replacing of consumables conveniently. Use temperature control system to get the data of time of storage, ambient temperature, and watt in the process of the temperature control in an electronic file through the display. The advantages of the temperature control system are the function of slowly heating at high temperature, over-temperature protection and monitoring at constant temperature.

![Figure 3. Quick coupling at level of nuclear energy.](image-url)
2.4. Safety analysis

The loads applied to the storage container include:

- The inner pipe is pressurized by filled helium;
- The outer pipe is vacuumed;
- Static load of system (including weight of the perforated pipe loaded nuclear fuel).

Because the storage container is planned to be set on the working platform in the hot cell statically, and there is no external load applied to the storage container during storage, it is not need to consider other source of loads such as shear stress, torsion stress, bending moment, and periodic loaded. During the period of the simulated storage, the pressure of the filling gas in the storage container is kept constant to avoid the formation of an environment which leads component to oxidization in the storage container. Besides, there is no periodic load on the storage container, so fatigue issue can be ignored. After the storage container is assembled, the outer pipe, inner pipe, and weld bead needs to be subjected to force analysis as below mentioned.

2.4.1. Safety analysis of pressurization of inner pipe. The test pressure in the inner pipe is 22 psig = 151,685 Pa = 0.152 MPa ($\sigma_{T1}$). As shown in Figure 6 and 7, calculate the circumferential stress ($\sigma_1$), longitudinal stress ($\sigma_2$) and maximum shear stress ($\tau_{max}$) of a thin-walled cylinder which diameter is 6 inch according to the value of the internal pressure calculated ($\sigma_{T1}$) as equation (1), (2) and (3):

\[
\sigma_1 = \frac{\sigma_{T1}D}{2t} = \frac{(0.152 \times 210.7) / (2 \times 2.8)}{2.8} = 5.72 \text{ MPa (tensile stress)}
\]

\[
\sigma_2 = \frac{\sigma_{T1}D}{4t} = \frac{(0.152 \times 210.7) / (4 \times 2.8)}{2.8} = 2.86 \text{ MPa (tensile stress)}
\]

\[
\tau_{max} = \frac{\sigma_1 - \sigma_2}{2} = \frac{5.72 - 2.86}{2} = 1.43 \text{ MPa}
\]

Calculate the safety factor of the thin-walled cylinder based on the maximum stress value obtained above as equation (4):

\[
\text{Safety factor } SF = \frac{E}{\sigma_{max}} = \frac{206.9}{5.72} = 36.2
\]

According to the obtained safety factor equal to 36.2, the value is much greater than 1. As a result, the thin-walled cylinder made of 6-inch stainless steel pipe is safe during the process of bearing 19 psig internal pressure.
2.4.2. Safety analysis of outer pipe in vacuum. As shown in Figure 8 and 9, the vacuum insulated layer which is ring-shaped interlayer of the storage container is composed by an 8-inch and a 6-inch stainless steel pipe. Condition of vacuum in the interlayer is to avoid the heat loss of the inner pipe. The maximum degree of vacuum is 3 torr, and the hot cell space is at one atmosphere equal to 760 torr. In this safety analysis part, we take a conservative estimate that chose -760 torr as pressure to analyse the safety as equation (5):

$$\sigma_{T2} = PA = -760 \text{ torr} = -0.1 \text{ MPa (compressive stress)}$$  (5)

We calculated circumferential stress as equation (6):

$$\sigma_3 = (\sigma_{T2} t)/h = (-0.1 \times 2.8)/45.5 = -6.15 \times 10^{-3} \text{ MPa (compressive stress)}$$  (6)

Then, we calculated longitudinal stress as equation (7) and other results as equation (8), (9) and (10):

$$\sigma_4 = \sigma_{T2} \times [\pi (r_2^2 - r_1^2)]/(r_2t) = -0.1 \times [\pi (105.35^2 - 82.6^2)]/(105.35 \times 2.8) = 45.54 \text{ MPa (compressive stress)}$$  (7)

Safety factor $SF = S/\sigma_{\text{max}} = 172.4/45.54 = 3.8$  (8)

Maximum shear stress $\tau_{\text{max}} = (\sigma_3 - \sigma_4)/2 = (45.54 - 6.15 \times 10^{-3})/2 = 22.77$  (9)

Safety factor $SF = 0.5S/\tau_{\text{max}} = (0.5 \times 172.4)/22.77 = 3.79$  (10)

According to the obtained safety factor value, the thin-walled made of the 8-inch stainless steel outer pipe and the 6-inch stainless steel inner pipe in an annular cylinder space are in a safe situation while being subjected to external pressure.

![Figure 8](image1.png)  Schematic diagram of the internal pressure and circumferential stress in the vacuum insulated layer.

![Figure 9](image2.png)  Schematic diagram of the internal pressure and longitudinal stress in the vacuum insulated layer.

2.4.3. Safety analysis of weld bead. When the strength of the welding rod matches the strength of the steel, the 6-inch stainless steel inner pipe are subjected to internal pressure, and $F$ is the force applied by the inner pipe to the end plate of the storage container as equation (11):

$$\sigma = F/A \rightarrow 0.152 = F/(\pi/4 \times 159.6^2) \rightarrow F = 3,040.9 \text{ N}$$  (11)

The tensile force exerted on the weld bead is 3,040.9 N. According to the length of fillet weld, calculate the shear stress that the weld bead can withstand when the 6-inch inner pipe are subjected to internal pressure as equation (12):

$$\sigma = My/I = 32M(D^2+2t)/[\pi[(D+2t)^4-D^4]] = (32 \times 1,354,985 \times 165.2)/[\pi[165.2^4-159.6^4]] = 23.8 \text{ MPa}$$  (12)

Safety factor $SF = 205/23.8 = 8.6$  (13)

As the length of the welding leg is up to 2 mm, the obtained safety factor value as equation (13) is much greater than 1, and the thin-walled cylinder made of 6-inch stainless steel pipe is in a safe situation.

2.5. Characteristics of manufacture

- Stainless steel ball valve: We changed the design of ball valve by cutting the flange end at one side, and then the bell mouth is welded. It is convenient to insert and pull out fuel rod in the storage container.
- Perforated pipe: In order to load fuel rods and conduct heat effectively, a seamless stainless steel pipe with an outer diameter of 18 mm is chosen. A CNC drilling machine is used for drilling the surface of perforated pipe, and then removing of burrs repeatedly is important to prevent the burrs of the metal generated by the cutting process from damaging the surface of the fuel rod.
- Supporting plate and end plates with six holes: A measure of temperature can reach a maximum operating temperature of 500°C in the storage container. In order to avoid thermal expansion caused by the heating the components, the entire storage container is assembled by welding.
process, except the perforated pipe and the support plate are not fixed by welding for reserving space for thermal expansion. The end plates with six holes and the 8-inch outer stainless steel pipe are also sealed with an O-ring to maintain the tightness.

2.6. Testing requirements
The test for storage container includes heating test, vacuum test, helium Leak Testing and simulated insert and pull out test for fuel rod described as below.

- **Heating test:**
The heating layer of the inner pipe is heated, and the temperature measuring rod detect the ambient temperature in the container. Then, use temperature control system to get the data of time of storage, ambient temperature, and watt in the process of the temperature control in an electronic file. Acceptance Criteria is filling the storage container with helium gas and heat the storage container at three stages including 100, 250 and 500°C. Finally, record the time of storage, ambient temperature in the storage container, and watt in the process of the temperature control in an electronic file.

- **Vacuum test:**
Vacuum process is performed on the vacuum insulated layer of the outer pipe, and the vacuum degree in the container will be recorded. Acceptance criteria is that as the pressure reaches 3 torr, stop the vacuum process and keep it for 10 minutes. The internal pressure in the storage container is not greater than 10 torr. Finally, record the time and vacuum degree with an electronic file.

- **Helium Leak Testing:**
The heating layer in the inner pipe is pressurized at the test pressure of 19 psig (+3, -0), and maintained the pressure for 10 minutes. The acceptance criteria is no leakage at any position on the weld bead.

- **Simulate insert and pull out test for fuel rod:**
A simulated fuel rod with a diameter of 13 mm, a length of 4 m, and a weight of more than 3 kg can be transported into the storage container through ball valves. Verify if the simulated storage container meet the requirement of functional of transport and carry fuel rods into storage container.

3. Test results and discussion
The test results of the storage container are shown as below:

- **Heating test:**
Fill the storage container with helium gas and heat the storage container at three stages include 100, 250 and 500°C, respectively. All the specified temperature value can meet requirement, and then the storage container passed the heating test as shown in Figure 10.

- **Vacuum test:**
After the pressure reaches 3 torr, stop the vacuum process and keep it for 10 minutes. The internal pressure in the storage container is not greater than 10 torr. This result is satisfied and shown in Figure 11.

- **Helium Leak Testing:**
The heating layer in the inner pipe is pressurized at the test pressure of 19 psig (+3, -0), and maintained the pressure for 10 minutes. There is no leakage at any position on the weld bead. This experiment result is satisfied and shown in Figure 12.

- **Simulate insert and pull out test for fuel rod**
A simulated fuel rod can be transported into the storage container through ball valves. With a satisfied result meets the requirement of functional of transport and carry fuel rods into storage container as shown in Figure 13.
4. Conclusion
After the storage container is completed, all the test mentioned in section 2.6 has passed with a satisfactory test result. Confirming the design and manufacture can fully meet the functions of helium filling, maintaining vacuum insulated layer, and heating. In Addition to, it is also not deformed due to expansion and thermal stress meet the required functions. To meet the requirements mentioned in section 2.1 and design described in section 2.3, storage container including the following features is necessary:

- To maintain vacuum air tightness, the vacuum insulated layer of the outer pipe install an O-ring with filling materials which can keep adiabatic condition instead of welding process. This feature provide the 6-inch inner pipe has the capacity for thermal expansion.
- The perforated pipe and the supporting plate are not fixed by welding process, and some gaps are reserved for thermal expansion. Therefore, the perforated pipe can slide between the supporting plates after being heated.
- Three support plates are added to each section of the perforated pipe to prevent displacement of the perforated pipe, thermal deformation, and to keep the perforated pipe at fixed position.
- The heating speed is relatively slow and enlarge the holding time.
- The temperature control system controls the power of heater and time effectively to keep the temperature in the storage container within the specified range. As a result, heat is conducted evenly to the components in the storage container.

References
[1] ASTM, A-240 TYPE 304
[2] PNL-6365, Evaluation of Cover Gas Impurities and Their Effects on the Dry Storage of LWR Spent Fuel, Pacific Northwest Laboratory, Richland, Washington, November, 1987
[3] CNS 9801, Pressure and leak for pressure vessels
[4] Standard of Safety Inspection for Pressure Vessel, Article 12, Section 2, Chapter 2
[5] CNS 12661, Method of Test for Liquid Penetrant and Classification of Indication
[6] CNS13021, Method of visual test for the welds of steel structure
[7] CNS 9788, Pressure vessels (General standard)