Verification Tests on Cask-Storage Method for Storing Spent Fuel at Reactor

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INTRODUCTION

In Japan, the cask-storage method of spent fuel will be licensed in the near future and the related R & D works (partly of the Japanese Government) have been carried out mainly by CRIEPI. This paper describes the results of research subjects that CRIEPI selected in order to provide reference data for the licensing of the cask-storage method as follows : (1) Temperature Analysis & Tests of Fuel Cladding, (2) Creep Test of Fuel Cladding, (3) Containment Test of Cask Lid Structure, (4) Cask Drop Test, (5) Material Testing of Ductile Cast Iron Cask, (6) Building Collapse & Heavy Objects Drop Accident on to Cask, (7) Cask Toppling by Earthquake.

SAFETY EVALUATION ITEMS OF CASK-STORAGE METHOD

Fig. 1 shows a design concept of the cask-storage method that CRIEPI developed for study purpose. Fig. 1 also shows seven research subjects that CRIEPI considered necessary for the licensing of the cask storage method.

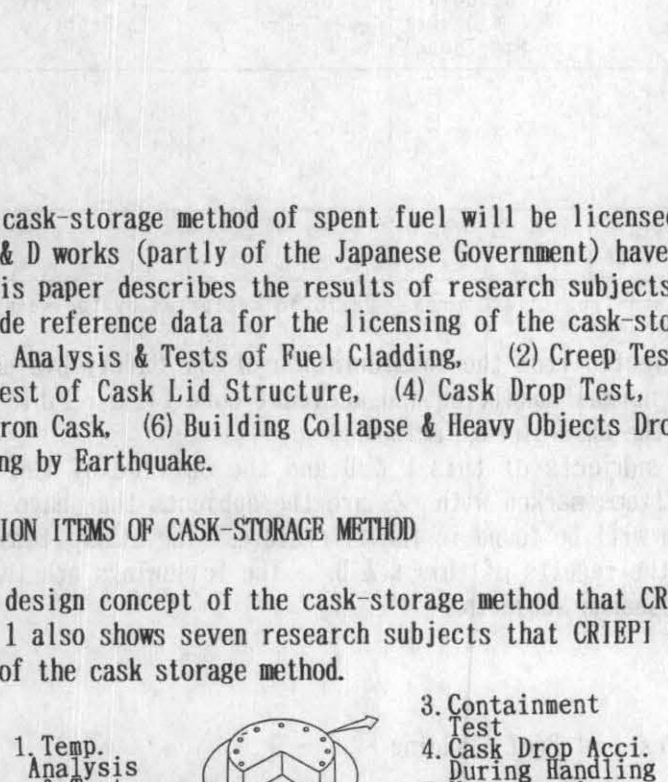


Fig. 1 R & D Subjects on Cask Storage Method

Table 1 Safety Evaluation Items of Cask Storage Method

Function & Place / Major Phenomena	Heat Removal	Containment	Subcriticality	Shielding	Struc. Strength
	· Cask · Building	· Fuel Cladd. · Cask Lid	· Fuel Basket	· Cask · Building	· Cask
Normal Condition · During Storage	○Max Temp. of Cladding ○Cask Body ○Envir. Temp.	○Integrity of Cladding & Lid Gasket (Max Temp.)	△Subcritical. △Durability of Neutron Absorber	△ Shielding △Durability of Neutron Moderator	△Structural Design
Accident Condition · Cask Drop		○Integrity of Lid	○Integrity of Basket	△☐ Shielding	○Integrity Against Impact
· Bldg. Collapes by Earthquake	○Temp. Rise in Debris	○Integrity of Cladding & Lid Gasket (Max Temp.)		○Temp. Rise of Pb Layer in Debris	○Integrity Against Impact
· Cask Toppling by Earthquake					○ Toppling (Need of Tie-down) ☐Integrity Against Impact
· Misc.	☐Temp. Rise by Vent. Close				

○:Subject of this R&D, △:Found from Literature, ☐:To be Evaluated by the Results of this R&D.

The seven subjects were selected from the consideration of the Safety Evaluation of the cask-storage method under normal condition and accident condition. Table 1 shows the Safety Evaluation Items of the cask-storage method.
Items marked with ○ are subjects of this R & D and the outline of the results are described in this paper. Items marked with △ are the subjects that have been already studied and the information will be found in the literature. The other items marked with ☐ will be evaluated by the results of this R & D. The followings are the outline of the results of the seven research subjects.

OUTLINE OF THE RESULTS

(1) Temperature Analysis & Tests of Fuel Cladding

It is important to develop a precise temperature analysis code of the fuel cladding to design and evaluate a dry storage cask as shown in Fig. 1, so as to maintain the surface temperature of the fuel cladding under the maximum allwable temperature as required during the stoarge period. CRIEPI modified and developped the conventional finite element analysis code "ABAQUS" to analyze the surface temperature of fuel cladding by taking account of convection of Helium gas in the dry cask. The code "ABAQUS" was verified by a heat transfer test using a full-scale (100-ton class) cask.

Fig. 2 shows results of the analysis and the test giving a good agreement of the analysis and the test. The cask used for the test was a stainless steel/lead type dry cask (MSF-IV) and contained simulated 21 PWR spent fuel assemblies with a maximum burn-up of 48,000MWD/tU, 5-year cooling time after discharge from reactor and a heat of 23 kW/cask. The maximum measured temperature of the fuel suface was under a design temperature (approximately 380 ℃), and the validity of the cask design for heat removal was verified (Yamakawa et al 1992, Gomi et al. 1992).

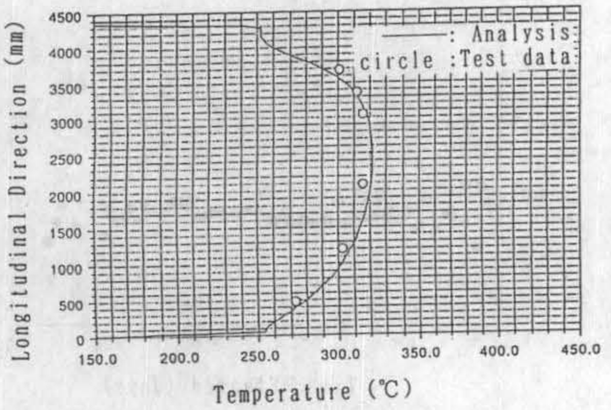


Fig.2 Results of Temp. Analysis and Test of Fuel Cladding in the Longitudinal Direction of the Cask(Vertical, He atomosphere)

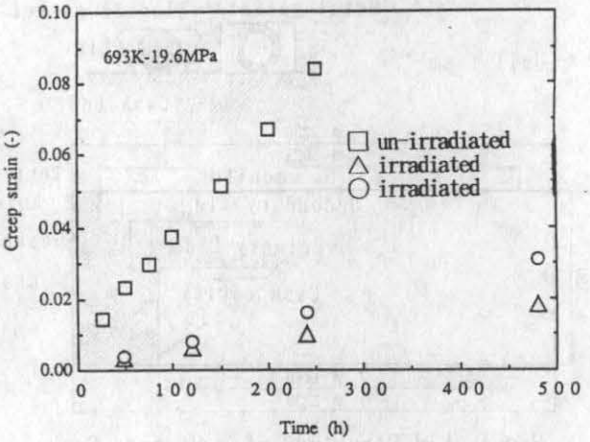


Fig.3 Results of Creep Tests of Zircaloy

(2) Creep Test of Fuel Cladding

In order to ensure the integrity of spent fuel during storage, it is necessary to sustain the creep deformation due to the internal pressure and the heat of the fuel rod within a certain value. Because there are few data on creep of the irradiated Zircaly for fuel rod, CRIEPI carried out the creep test of irradiated Zircaloy tube specimen taken from PWR spent fuel (17x17, average Burn-up 46,000MWD/tU). In addition, CRIEPI carried out creep tests of unirradiated Zircaloy tube, thereby developed a method to evaluate the maximum allowable temperature of fuel cladding during storage (Mayuzumi et al. 1989, 1990).

Fig.3 shows an example of the creep test data of Zircaloy tubes. From Fig.3, the followings can be said: ① The creep strain of the unirradiated fuel cladding is larger than that of the irradiated one. ② The irradiated fuel cladding does not rupture, even if the creep strain exceeds more than 1%.

The temperature of the fuel cladding due to the decay heat will decrease with time, thereby the the strain rate of the steady-state creep will slow down and saturate at several years after the start of storage. CRIEPI developed a calculation formula of the creep strain with storage time and obtained the maximum (initial) temperature for storage so that the accumurated creep strain will not exceed a certain value (e.g. 1%) through the storage period (e.g. 40 years). For example, the maximum temperature to store the PWR fuel as shown (1) (5 years after discharge from reactor) will be approximately 380 ℃.

(3) Containment Test of Cask Lid Structure

The containment barrier of the storag cask is the metallic gasket in the cask lid structure and should be integral during the storage period (e.g. 40 years). Fig.4 shows an example of the lid structure. Normally, the storage cask has a double lid structure and each lid has two gaskets (one metallic gasket and one elastic gasket in the case of Fig.4). The metallic gasket contains a spring made of stainless steel or Inconell, and the spring is covered with aluminium or silver (O.Kato et al. 1992).

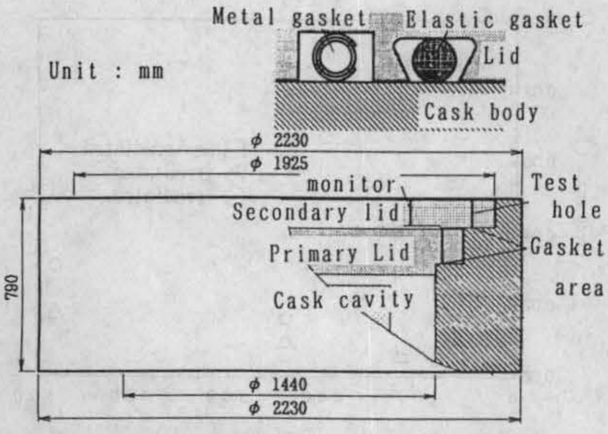


Fig. 4 Lid Structure of a Storage Cask

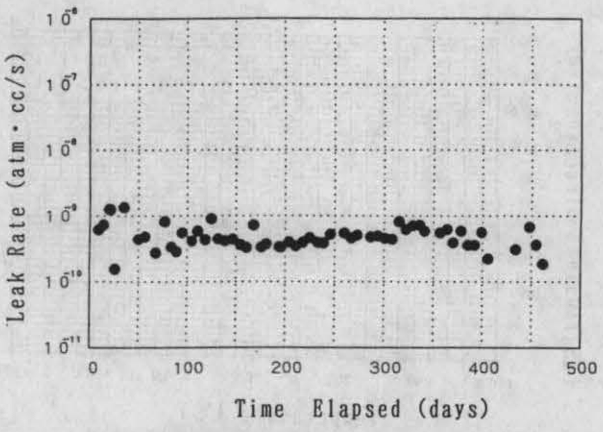


Fig. 5 Results of Containment Test

There are no data found in the literature on the long-term containment capability of the metallic gaskets. CRIEPI, therefore, carried out the long-term containment test of the metallic gasket using full-scale lid structure (two kinds) of the storage casks. Fig. 5 shows the test results up to 450 days showing the integrity of the containment capability.

(4) Cask Drop Test

It is the characteristic of the storage cask that the cask may be handled without shock-absorber (impact-limiter) in the storage building of which floor will be made of reinforced concrete slab. Therefore, it is important to study and evaluate wheather the cask, if accidentally dropped onto the reinforced concrete floor during handlng, could keep its integrity or what would be the maximum allwable height for accidental drop without losing the integrity of the storage cask.

CRIEPI carried out tests and analysis of the cask drop accidents using 100-ton class casks (Ductile Cast Iron Casks : CASTOR-V, TN-1300, NKK S/T) for vertical drop, horizontal drop and corner drop. Fig. 6 shows the results of deceleration measurements as a function of the drop height. It shows that the degree of the energy absorption by concrete floor will change with the drop height. The value of the deceleration will not linearly increase in proportion to the drop height.

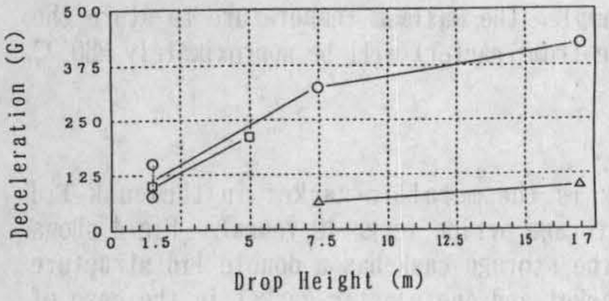


Fig. 6 Test Results on Drop Height & G-Value

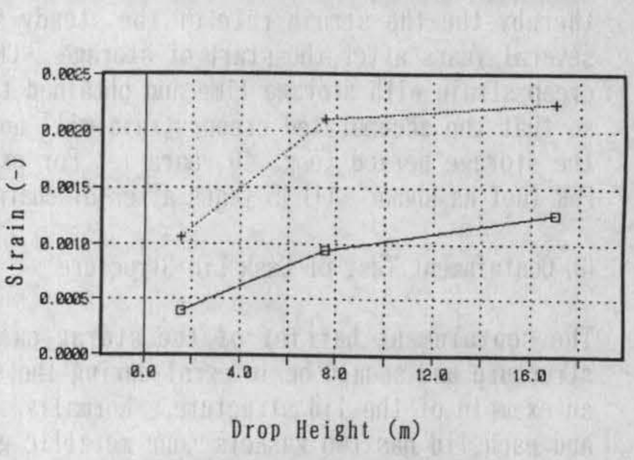


Fig. 7 Strain of Cask Body as Function of Drop Height plus:analysis, square:test

(6) Building Collapse & Heavy Objects Drop Accident onto Cask

Generally, storage casks are deisgned on the basis of transport casks of which structural strength is strong enough to maintain their integrity under the accidental test condition of 9 m drop onto unyielding target. Therefore, CRIEPI considered that the building (e.g. Fig.1) storing the storage casks can be designed to be simple and less strong structure against earthquake (e.g. Class C structure according to the Japanaese Classification for Seismic Degree).

CRIEPI made analysis and its verification test using a full-scale cask (100-ton class DCI cask; CASTOR V) on wheather or not the integrity of the storage cask can be maintained if heavy objects such as the concrete roof of the storage building fell down onto the storage cask due to a hypothetical building-collapse by earthquake(Ito et al. 1992, Y.Kato et al. 1992).

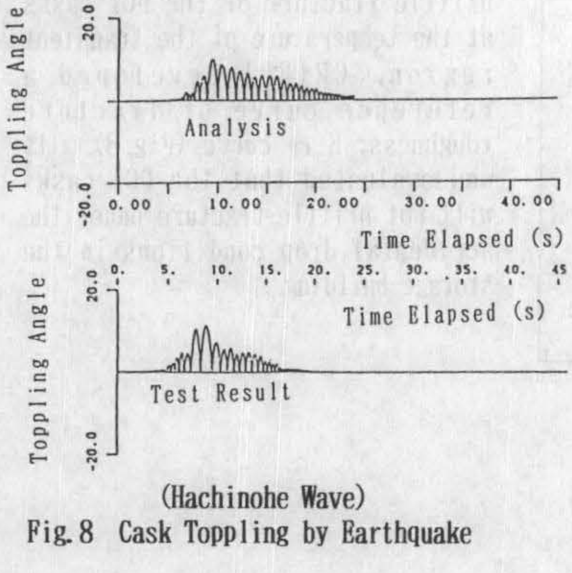
The major results are as follows :

① The simple storage building designed by the criteria of the Class C will not collapse by the strongest dynamic-earthquake-wave (i.e. Class S_2 according to the Japanaese Classification for Seismic Degree) according to the analysis by CRIEPI. Even though, CRIEPI assumed a hypothetical collapse of the building and a hypothetical drop of the roof made of 16 cm thick reinforced concrete from the height of 17 m, as the maximum test condition for the storage cask.

②According to the results of the analysis using DYNA-3D code and the test using the full-scale cask, there was no leakage from the cask lid area and no stress larger than the yield stress was generated in the cask body; thereby the cask would maintain its integrity even if the building might collapse.

(7) Cask Toppling by Earthquake

During the storage period, the storage casks may be placed vertically or horizontally. It will save land area if the casks are placed vertically. In that case, the cask should be evaluated if they would topple down by a strong earthquake or they need tie-down to the ground. CRIEPI made analysis and tests to know the toppling condition of the cask by the earthquake.



(Hachinohe Wave)

Fig.8 Cask Toppling by Earthquake

Table 3 Analytical Results on Cask Toppling

Wave	Acceleration (gal)		Toppling Angle** (deg.)
	Horizon.	Vertical	
S_2	354 342	213 205	0.4 1.1
El Centro	342 683 *	206 413 *	2.0 7.1
Hachinohe	203 406 *	150 299 *	0.0 5.4

* Hypothetical Conditions
** Critical Toppling Angle : 17 deg.

Fig. 7 shows the results of the analysis of the impact strain generated at the cask body using the three-dimentional impact analysis code "DYNA-3D" and the tests using the full-scale casks (100-ton class). From these results and the measurements after the drop tests, the followings can be said :

① In the secondary lid area after the drop tests up to 17 m, the analysis predicted no plastic strain and the leak test found no leakage.

② In the primary lid area after the drop tests up to 1.5 m, the analysis predicted no plastic strain and the leak test found no leakage.

③ On the other hand, the analysis predicted plastic strain and the leak test found leakage in the primary lid area after the drop tests from the height of 7.5 m and 17 m

④ The analysis always predicted more conservatively than the test results.

⑤ The integrity of the full-scale casks were verified for the postulated drop accident for the maximum lifting height that was determined by the normal handling procedure and the building design as shown in Fig. 1.

⑥ It was verified that the storage casks have enough safety margin for the drop accident in the storage building as shown in Fig. 1 because the limiting drop height for the casks to maintain their integrity is very high (e.g. higher than 17 m for vertical lifting) (Ito et al. 1992, Y. Kato et al. 1992).

(5) Material Testing of Ductile Cast Iron Cask

Ductile Cast Iron (DCI) Casks have not yet been licenced in Japan. CRIEPI carried out material tesings using specimens sampled from three full-scale DCI casks and seven model DCI casks with real diameter and thickness, in order to establish a data-base required for licensing. The results are as follows (Arai et al. 1992):

① There were no large scatterings in the materials data distribution and all the properties satisfied the Japanese Industrial Standard JIS G 5504 "Heavy-walled ferritic spheroidal graphite iron castings for low temperature service".

② The Charpy Impact Value Curve as a function of temperature showed a ductile/brittle transient region at around -20℃.

③ In order to make an evaluation of brittle fracture of the DCI casks at the temperature of the transient region, CRIEPI developed a reference curve of fracture toughness; K_{IR} curve (Fig. 8). It was evaluated that the DCI casks will not brittle fracture under the accidental drop conditions in the storage building.

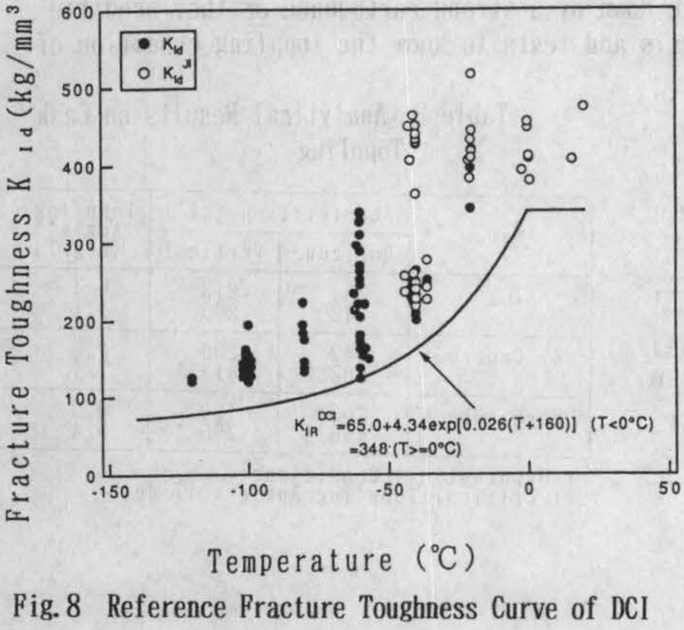


Fig. 8 Reference Fracture Toughness Curve of DCI

Fig. 9 shows a result of the analysis using a code "UDEC-CASK" and a test result using a scale-model (ratio : 1/5) of the storage cask against an earthquake of a long wave-length that is ever experienced in the past in Japan (so-called "Hachinohe Wave"). They showed a good agreement between the analysis and the test.

Table 2 shows the analytical results of toppling angle of the cask by the simulated wave of the strongest earthquake ever experienced in Japan and the hypothetically magnified earthquake. It was shown that the toppling angle would not reach the critical toppling angle of 17 degree, thereby the cask will not topple down by the earthquake and need not tie-down.

CONCLUSION

(1) The evaluation methods of the safety of the cask-storage method under normal and accident conditions were developed.
(2) The safety of the cask-storage method under normal and accident conditions was verified using full-scale (100-ton class) casks .

The results of the present study will provide much data for licensing the cask-storage method.

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