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Development of Fuel Debris Canister -Structural Verification Test using a Full-Size Mock-Up Canister-

Kazuma Hirosaka[1], Hideaki Uchiyama[2], Toshihiro Matsuoka[3], Yasufumi Miyahara[4], Yuichi Matsushita[5], Kohei Ono[6], Taichiro Yamada[6]

[1] Researcher, IRID/ Hitachi-GE Nuclear Energy Ltd., Japan (kazuma.hirosaka.zp@hitachi.com)
[2] Deputy General Manager, International Research Institute for Nuclear Decommissioning (IRID), Japan
[3] Engineering Manager, IRID/Mitsubishi Heavy Industries, Ltd., Japan
[4] Specialist, IRID/Toshiba Energy Systems & Solutions Corporation, Japan
[5] Unit Manager, IRID/ Hitachi-GE Nuclear Energy Ltd., Japan
[6] Staff Engineer, IRID/ Hitachi-GE Nuclear Energy Ltd., Japan

ABSTRACT

For decommissioning of Fukushima Daiichi Nuclear Power Station (hereinafter called the 1F), technology for containing, transfer and storage of fuel debris in a safe and effective manner is required. Retrieved fuel debris contains nuclear fuel material, then, it will be put into specialized containers (canisters) and handled by the canister. It is necessary to consider the confinement of radioactive materials and sub-criticality in the handling of the debris, thus theses performance of the canister in accidental events should be evaluated.

Three drop tests were conducted, 9 m canister drop in a vertical position and oblique position, and 7 m canister drop in a vertical position on another canister. Full-size mock-up canisters were used, and we measured the displacement of the lid, which is related to the containment function of the canister and the deformation of the body, which is related to function of canister subcriticality. We confirmed from the test results that the canister maintains the safety functions such as containment function and subcriticality function at the drop events. We also conducted a structural analysis simulating the test conditions using the finite element analysis code LS-DYNA and compared the simulation results with the test results. Structural analysis showed good agreement with the test results in the behaviour of the mock-up canister. It was also confirmed that the displacement of the lid and the deformation of the body obtained in the analysis have good agreements with the test results.

We concluded that the structural integrity of the canister at the assumed drop events has been confirmed by the structural verification tests. In addition, we confirmed the applicability of the structural analysis method by comparing the analysis results with the test results.

INTRODUCTION

International Research Institute for Nuclear Decommissioning (IRID) has been developing a fuel debris canister to establish the technology for containing, transportation and storage of the fuel debris which will be retrieved from the 1F. The fuel debris canister is required to maintain the structural integrity over the entire design life and the drop event is the most severe condition, which should be evaluated to see if it maintains. There are two purposes in this study. One is to confirm the structural integrity of the canister at a drop event. The other is to check the applicability of the structural analysis method to evaluate the integrity at the event. The results obtained under "The Subsidy Project of Decommissioning and Contaminated Water Management (Development of Technologies for Containing, Transportation and Storage of Fuel Debris)" granted by the Ministry of Economy, Trade and Industry.

Event selection for structural integrity evaluation

To develop a fuel debris canister, we first extracted some drop events from each operation of the latest canister handling flow (side-access retrieval method, dry storage, storage in metal casks) as the subject of the event selection. Among the identified design events and evaluation events, the events of the canister dropping in the vertical position, the canister dropping in the inclined position, and the canister dropping on the top of another canister in the vertical position were selected as the events for which the structural verification tests were performed.

The drop height was set with consideration of the dimensions of the building and transfer cask. The oblique angle was set to 60°, which has the largest impact in the preliminary numerical analysis with different oblique angles.

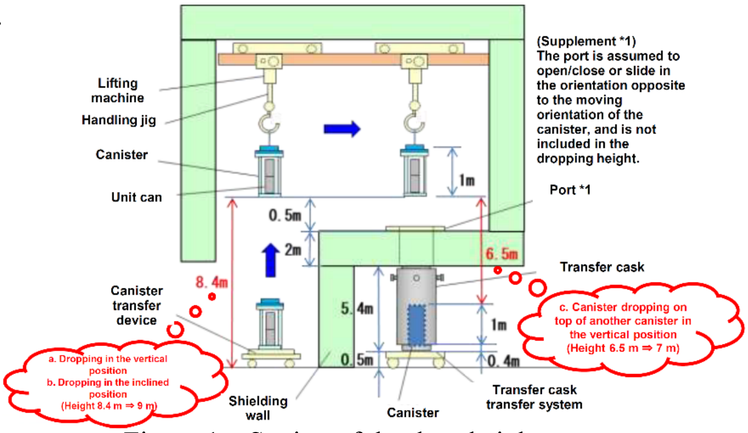


Figure 1 Setting of the drop height

Canister design

The canister design was developed on the basis of its design policy and design conditions with consideration of the latest canister handling flow and the status of other project study, in which further increasement of the amount of fuel debris retrieval per canister was considered. The canisters use stainless steel (SUS316L) with consideration of SCC resistance, procurement, workability.

For the lid, two types of lids were designed as remotely operable structures: a simple attachment structure that can be opened and closed by turning the lid, and a bolt structure that has a proven track record in remote controlled operation in TMI-2. The structure should not cause detachment of the lid or damage leading to a large amount of leakage and should not generate continuous leakage from the seal even when it receives an impact load such as a drop in the vertical position.

For vent mechanism, the diffusion evaluation of the hydrogen through the coupler and filter was conducted with assumption of the amount of hydrogen generated in the canister. Then, setting of the coupler inner diameter was determined. The amount of hydrogen was based on the test measurements in the presence of water and the actual amount will be reduced lower than the test measurements since the debri inside a canister will be dried. Additionally, on basis of risk evaluation for vent opening/closing during handling canisters, a regular opening coupler was adopted.

When fuel debris is dried in the unit can, the air supply mechanism is not installed in the canister, but when fuel debris is dried in the canister, air supply mechanisms is installed on the body flange at two locations (couplers for air supply). A coupler which is normally-closed was installed in each air supply mechanism so that hot air flows from the bottom to the top of the canister in the order of air supply coupler (air supply port), piping, inside the canister, air supply coupler (exhaust port). To prevent clogging, it was decided to install a filter on the system side equipment and not on the air supply coupler (exhaust port).

For body, two types of bodies were designed. Inner diameter of 220 mm is able to maintain subcriticality even if the debri stored inside the canister has the highest criticality. Inner diameter of 400 mm, which would be used after the intensive study of the actually retrieved debri from 1F and the confirmation of subcriticality, improves workability. The internal height of the canister was equal to the summation of the catalyst case thickness (20 mm (temporarily set)) and height of two unit cans (400 mm per can), with considering a margin for the thermal expansion of the unit cans, the manufacturing tolerance, the total height when the unit cans are stored at a tilt angle. A tapered shape is provided at the joint between the flange and the body, and between the body and the bottom plate to relieve stress when an impact load is applied.

Suspending part structure use a groove inside the lid of the canister for lifting and making the suspending device smaller than the outer diameter of the canister lid, which allows lifting without being affected by the shape of the storage space (square prism, cylinder, plate (drilled hole)) With this structure, the buffer structure does not interfere with the suspending part when a canister drop on another canister and the buffer structure of the top canister crush totally.

To ensure the confinement function at the storage facility during storage, elastomer gasket (EPDM: ethylene propylene diene rubber) is used. This selection prioritizes the storage efficiency (minimization of lid outer diameter), lid fastening workability, and applicability to a simple attachment structure. Sealing structures are installed both in upper and side of the top end of the body for a simple structure type lid, and only in upper of it for a bolt type lid. A sealing structure of the upper of the top end of the body is firmly attached to the structure of the port to prevent contamination of seal part as much as possible during the debri installation inside the canister. And also, an inner lid for the canister body (with a hydrogen venting filter) was installed to prevent contamination during handling of the canister including fastening the lid. For the filter, the hydrogen release was evaluated by using a hydrogen diffusion evaluation method, and it was confirmed that the hydrogen concentration was less than 4 vol% when using a wire mesh type stainless steel (SUS316) filter having a mesh diameter of 0.3 μm. Hydrogen flow is less affected by clogging because the large filter diameter is selected. Space for installing the catalyst was provided beneath the inside surface of the inner lid.

A buffer structure was installed under the bottom plate to prevent collision of installed items in the canister such as unit can to the inner surface of the lid due to the bounce back motion during drop events, and also to reduce deformation of the body of the canister. The skirt type buffer structure was selected because of its good manufacturability.

Eight types of structural concepts and drawings were developed for the canister: two types of lid structures (simple attachment structure and bolt structure), two types of inner diameter of body (220 mm and 400 mm), and with/ without air supply mechanism.

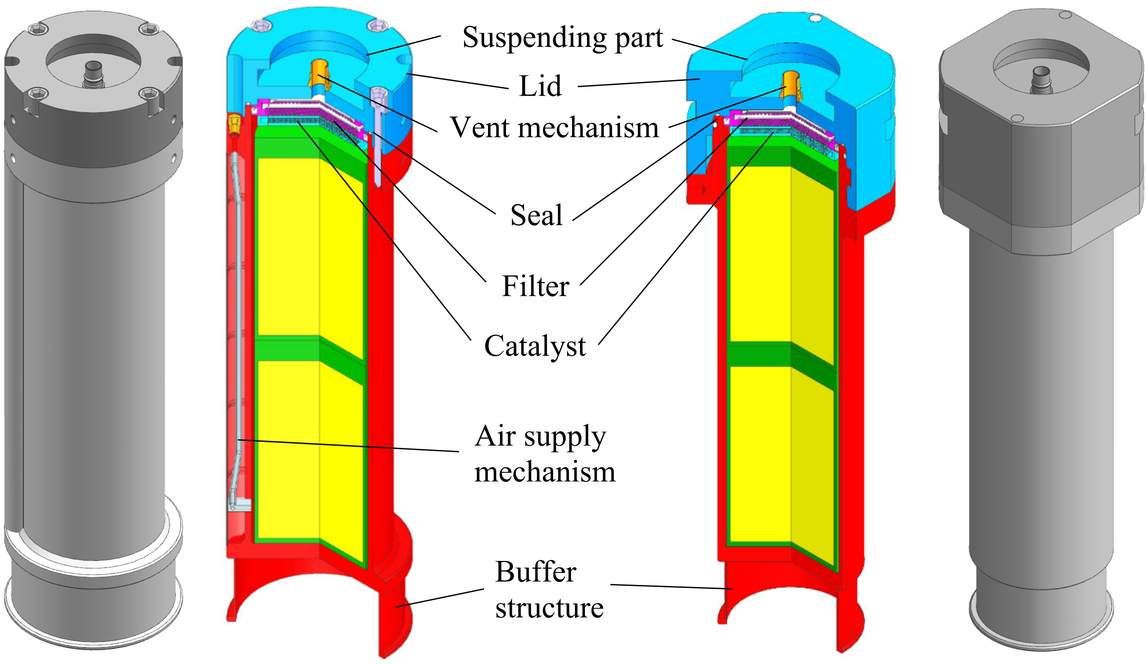


Figure 2 Canister structure (Left: Bolt type, Right: Simple attachment type)

DROP TEST AND ANALYSIS

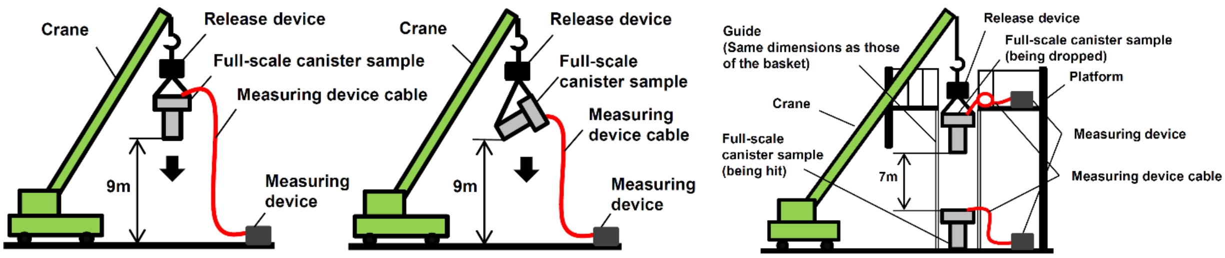
Drop test conditions

To evaluate the structural integrity of the canister, the following events which cause the severe impact on the structural strength of the canister were taken into consideration: a canister falling from a height of 9 m in a vertical position, falling from a height of 9 m in a 60° inclined position, and a canister falling from a height of 7 m and crashing onto the top of another canister in a vertical position.

A total of six structural verification test conditions were selected, which were based on the combination of the three drop scenarios and the structures of full-scale canister models. The establishment of a drop test site and measurement systems illustrated below were planned to reproduce events that may occur in operations at the 1F and to be used for structural verification tests.

Table 1 Test cases

No	Events	Test condition			Structures of full-scale canister models		
		Drop test height	Tilt angle	Number of tests	Lid structure	Body inner diameter	Air supply mechanism
1	Vertical drop	9 m	0°	1 for each lid structure	Simple attachment structure	400 mm	None
2					Bolt structure	220 mm	None
3	Oblique drop	9 m	60°	1 for each lid structure	Simple attachment structure	400 mm	Yes
4					Bolt structure	220 mm	Yes
5	Vertical drop on another canister	7 m	0°	1 for each lid structure	Simple attachment structure	220 mm	None
6					Bolt structure	400 mm	None



(a) Dropping the canister in a vertical position
(b) Dropping the canister in an inclined position
(c) Dropping a canister on another canister in a vertical position

Numerical analysis model and evaluating items for mock-ups drop test

Numerical analysis models to simulate drop events were developed, and how much the impact caused in these events affects the integrity of the canister was evaluated using the commercial finite element analysis code, LS-DYNA. The simulation models were developed based on the structural drawings of the canisters, and the impact velocity was set to the theoretical terminal speed of a free fall (e.g., = 13.3 m/s for the fall from the height of 9 m). Evaluation items are listed below;
(1) Confinement performance (effective plastic strain): The calculated values of strain must prove that there is no risk of fracture in the joint of the lid and the body. They must be less than the fracture equivalent plastic strain, for example, 30% for stainless steel (SUS316L).
(2) Confinement performance (seal gap displacement): A seal gap displacement must be within a range where proper compression allowances are maintained for the O-ring (0.8 mm for the top and 0.9 mm for the side). The occurrence of a momentary gap opening is permissible as the duration of leakage is minimal.
(3) Measures to maintain sub-criticality (maximum permissible change in the inner diameter of the body): The deformation of the body of the canister (change in its inner diameter) must be within a range (245 mm

or less, target is 232.5 mm or less) so that the geometric shape can maintain sub-criticality.

Table 2 shows the result of the structural analysis evaluation, and it was confirmed that all types of proposed structure design of a canister were robust enough to maintain their safety functions (such as confinement and criticality prevention) after being subjected in various events. In some test cases, a risk of the occurrence of a momentary gap opening was observed at the O-ring seal. Despite such cases, the confinement performance will be maintained because the duration of the gap opening is so short that leakage can be minimally suppressed.

Table 2 Structural simulation results

Events	Safety function	Evaluation items	Simple attachment structure				Bolt structure			
			Inner diameter: 220 mm		Inner diameter: 400 mm		Inner diameter: 220 mm		Inner diameter: 400 mm	
			Air supply mechanism							
			No	Yes	No	Yes	No	Yes	No	Yes
Vertical drop	Confine-ment	Plastic strain	○	○	○	○	○	○	○	○
		Seal gap	○	○	○	○	○	○	○	○
	Sub-criticality	Body de-formation	○	○	○	○	○	○	○	○
Oblique drop	Confine-ment	Plastic strain	○	○	○	○	○	○	○	○
		Seal gap	○	○	△:max 0.65mm	△ :max 0.83mm	○	○	△ :max 0.59mm	○
	Sub-criticality	Body de-formation	○	○	○	○	○	○	○	○
Vertical drop on a canister	Confine-ment	Plastic strain	○	○	○	○	○	○	○	○
		Seal gap	○	○	○	○	○	○	○	○
	Sub-criticality	Body de-formation	○	○	○	○	○	○	○	○

○: No problem, △: Risk of momentary gap

A total of 8 units of full-scale mock-up canisters were prepared with 6 different specifications. Two units were used for the vertical drop, two units were used for the oblique drop, and four units were used for the vertical drop on another canister. As for the contents of the canister (such as the unit can and fuel debris), weights whose external dimensions and weights were same as the contents were made. In addition, a cable entry flange was attached in each mock-up canister at a position that causes the minimum effect on the canister strength to guide the cables of a strain gauge and accelerometer installed inside the canister.

Test results

None of the mock-up canisters showed a coming off of the lid and cracks in the lid or the body (including the flange, body, and bottom plate) that ran through the thickness of those parts and created a leakage path after the tests. Leakage rates were below the acceptance criterion. There was no noticeable deformation in the body either. There was a case where the lid could not be removed after a drop test in an inclined position. The mock-up canister that showed this problem was with the simple attachment structure, an inner diameter of 400 mm with a ventilation mechanism. The cover of the air supply mechanism was bent and came to contact with the elbow. However, there was no damage in the piping.

As a result of the structural verification test, it was confirmed that all canister samples were robust enough to maintain their safety functions (such as confinement and criticality prevention) against the impact loads caused in the drop tests. In some test cases, a momentary gap opening may have occurred at the O-ring seal. However, the confinement performance should have maintained because the duration of the gap opening was so short that leakage should have been minimally suppressed. In addition, there was a case where the lid could not be removed after a drop test in an inclined position. The sample canister that showed such problem was with the simple attachment structure. This result has raised the need for continuous engineering efforts on the lid attachment method.

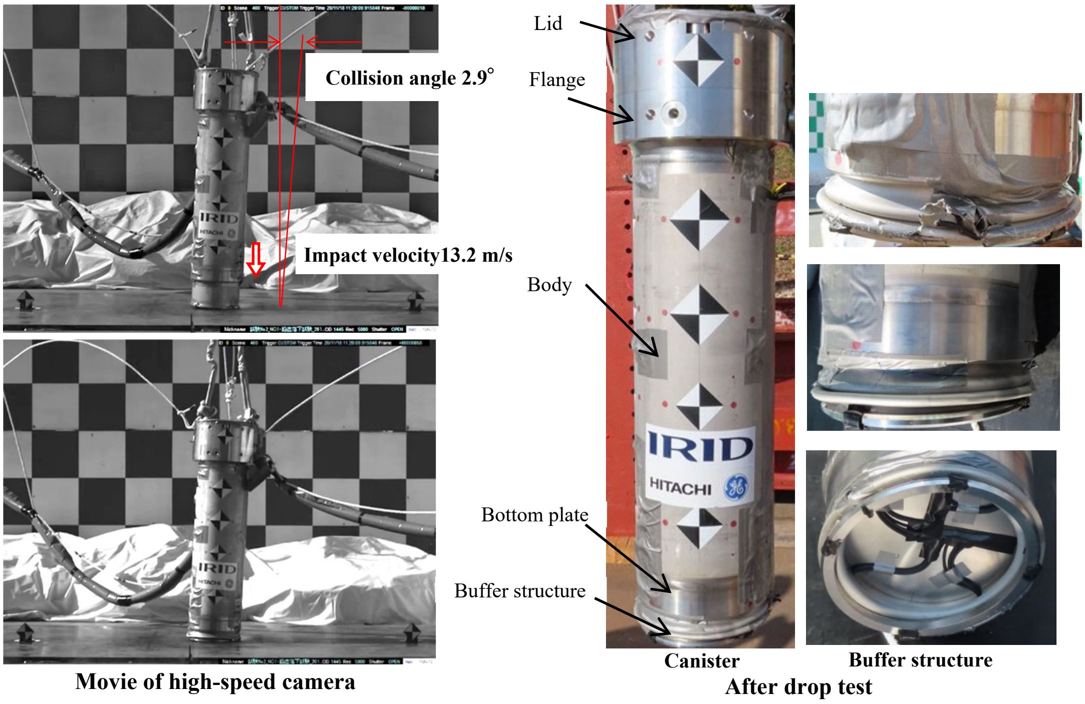


Figure 3 Result of the vertical drop test (Bolt type, inner diameter 220 mm)

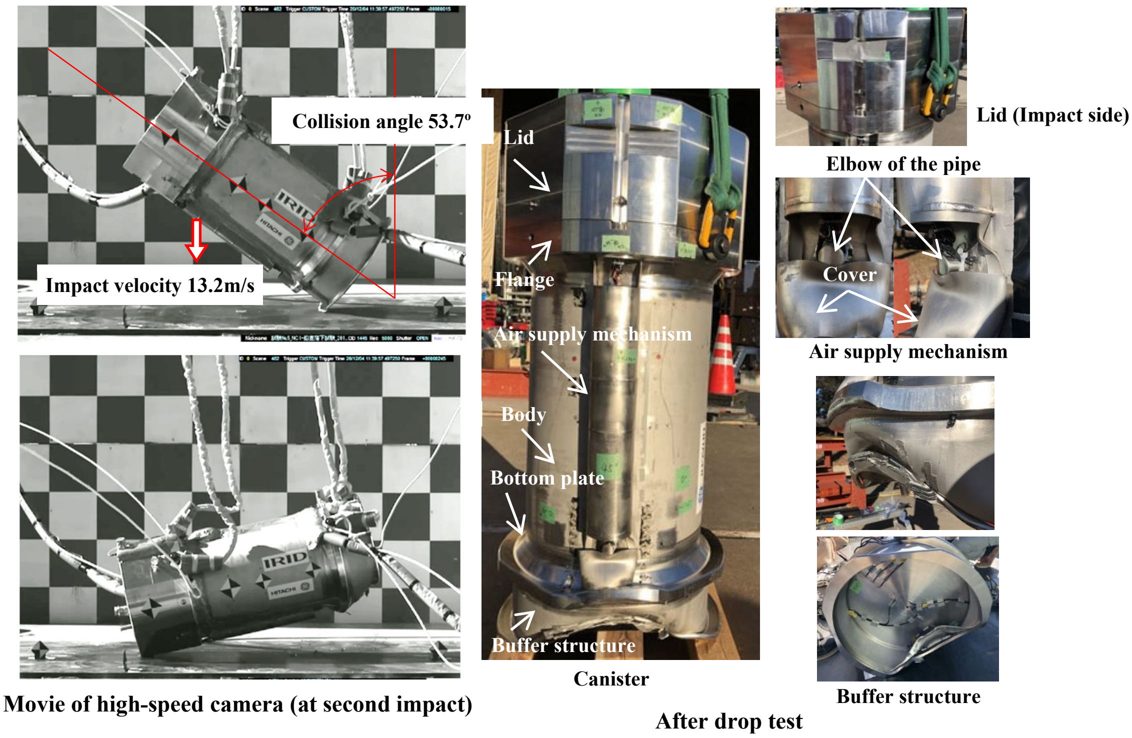


Figure 4 Result of the tilt drop test (Simple type, inner diameter 400 mm, with air supply mechanism)

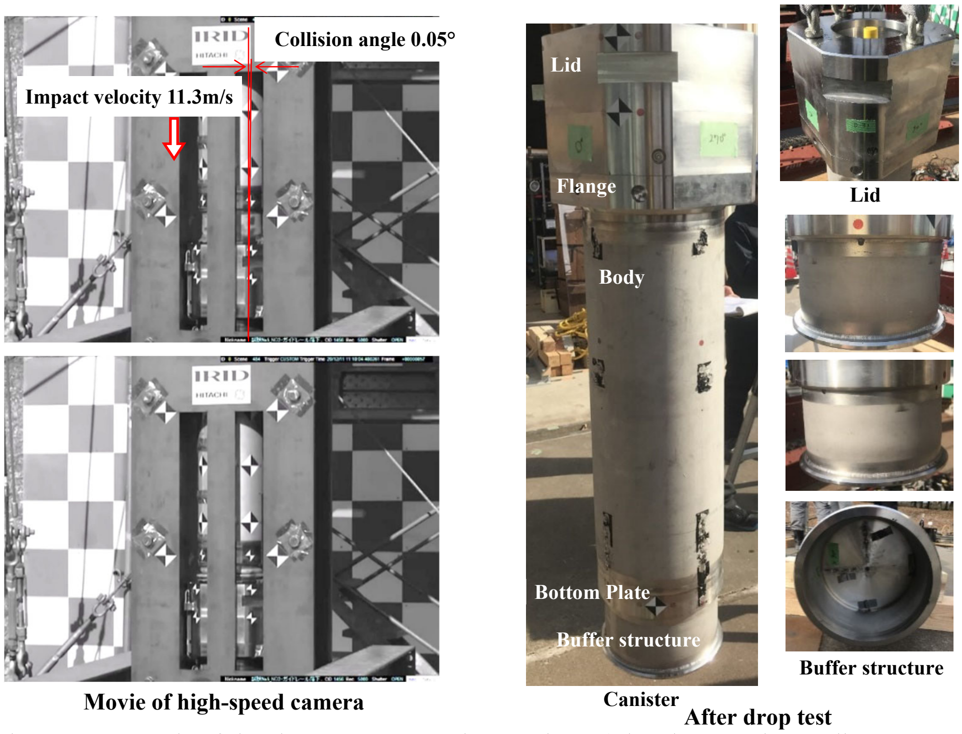


Figure 5 Result of the drop test on another canister (Simple type, inner diameter 220 mm)

Table 3 Summary of test results

Safety function	Check items	Test results							
		Vertical drop		Oblique drop		Vertical drop on another canister			
		Simple, inner diameter 400mm	Bolt, inner diameter 220mm	Simple, inner diameter 400mm	Bolt, inner diameter 220mm	Simple, inner diameter 220 mm		Bolt, inner diameter 400mm	
						Upper	Lower	Upper	Lower
Confine-ment	Leak test	○	○	○	○	○	○	○	○
	Visual inspection	○	○	○	○	○	○	○	○
	Strain (plastic deformation around O-ring groove)	○	○	– Missing data	– Missing data	○	○	○	○
	Momentary gap at O-ring seal (relative dis-placement of lid and body)	○	○	△ Occurrence of momentary gap	△ Occurrence of momentary gap	○	○	○	○
Criticality prevention	Measurement check (the inner diameter of the body)	○	○	○	○	○	○	○	○
Handling function	Removal of the lid	○	○	× Unable to open the lid	○	○	○	○	○

Structural analysis

A structural analysis that simulated the test conditions of the structural verification test was performed, and the result of the analysis was compared with the test result to evaluate the validity of the structural analysis.

It was conducted to evaluate the certainty of the analysis method (including analysis code, analysis model, and analysis conditions) that can simulate the structural integrity of the canister. The floor of the analysis model was configured to simulate the properties of the floor of the actual test facility, and the position of the canister during falling was set to be the same as that at the time of collision that had been recorded by a high-speed camera in the test. A theoretical value was used for the collision velocity since collision velocities were nearly equal to theoretical values in all test cases.

(1) Comparison of movements

Among the parameters that describe the movement of a mock-up canister in a drop test, those that were related to the energy consumption used for the deformation of the mock-up canister were compared to evaluate the reproducibility of the movement in an analysis model.

In a vertical position, the kinetic energy of the canister right before the collision was assumed to be all converted into the strain energy of the buffer structure in its most deformed state, and then it was converted into energy absorbed by the buffer structure due to its deformation and the kinetic energy of the canister's bouncing movement. The validity of the analysis of the impact load acting on the mock-up canister was examined by comparing the amount of the deformation of the buffer structure and the bouncing velocity obtained from the analysis with the test results. The difference in the maximum bouncing velocity was approximately 2% between the results from the test (1.53 m/s) and analysis (1.56 m/s), which suggested that the analysis accurately simulated the movement of the test in the drop in a vertical position.

When the canister was dropped in an inclined position, the buffer structure absorbed the kinetic energy in the primary collision, and then the mock-up canister turned to the inclined direction (rotational movement). The rotational kinetic energy of the mock-up canister right before the secondary collision produced by this rotational movement became the collision energy of the lid against the floor. The validity of the analysis of the energy transferred to the mock-up canister was examined by comparing the angular velocity and collision angle obtained from the analysis with the test results. The difference in the angular velocity was approximately 0.5% between the test (20.5 rad/s) and analysis (20.6 rad/s), and the angles of secondary collision were also nearly equal, which suggested that the analysis accurately simulated the movement of the test in the drop in an inclined position.

In the test of dropping a canister on another canister in a vertical position, the validity of the analysis of the impact load acting on the mock-up canister was examined in the same way as vertical drop denoted before by comparing the amount of the deformation of the buffer structure and the bouncing velocity obtained from the analysis with those obtained from the test. The difference in the maximum bouncing velocity was approximately 6% between the results from the test (1.35 m/s) and analysis (1.43 m/s), which suggested the analysis accurately simulated the movement of the test in a vertical drop on another canister.

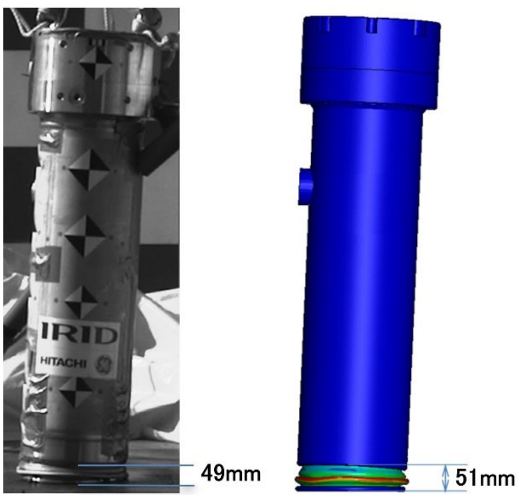


Figure 6 Comparison in the vertical drop test

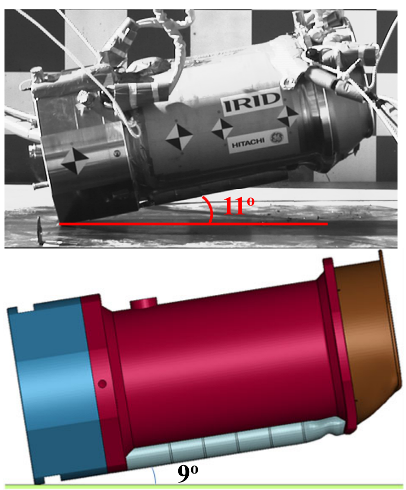


Figure 7 Comparison in the oblique drop test

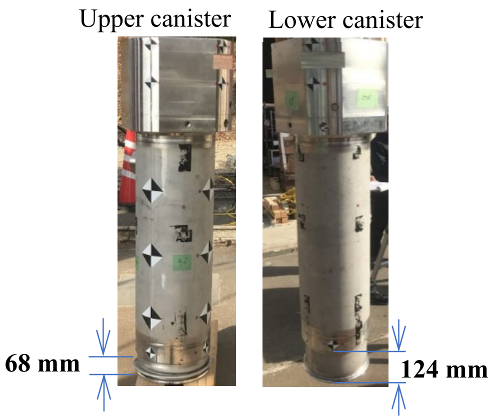
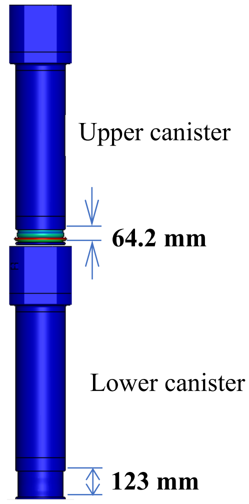


Figure 8 Comparison in the vertical drop test on another canister



(2) Result of the evaluation of the certainty of analysis related to safety functions

In vertical drop test, the relative displacement of the lid to the flange in an axial direction, which related to the confinement performance of the canister, was compared between those obtained from the test and the analysis. The maximum difference in the relative displacement of the lid to the flange in an axial direction was approximately 14% of the acceptable value.

Changes in the inner diameter of the body and its strain, which related to the criticality prevention performance, were compared between those obtained from the test and from the analysis. A significant difference was not found in changes in the inner diameter of the body between the results of the test and of the analysis. Strains in the central part of the body in a circumferential direction also showed similar results between the test and the analysis. These results suggested that the analysis could be used to evaluate the ability to maintain the criticality prevention performance.

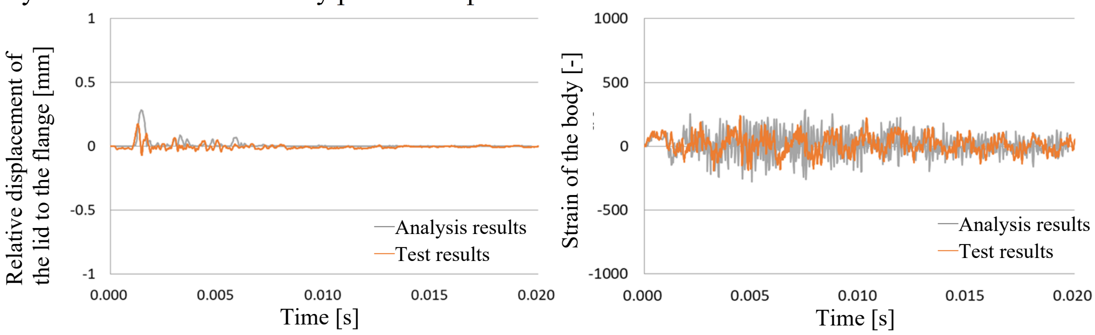


Figure 9 Comparison between the test and the analysis results in the vertical drop test

In the oblique drop test, the relative displacements of the lid to the flange in an axial direction and in a radial direction, which related to the confinement performance of the canister, were compared between those obtained from the test and from the analysis. The maximum differences in the relative displacement of the lid to the flange were approximately 44% of the acceptable value in an axial direction and approximately 11% of the acceptable value in a radial direction. The wave forms and the timings of displacement peak occurrence in the test result and analysis result well accorded with each other, which suggested that the post-test analysis accurately simulated the movement of the lid in both axial and radial directions. The margin for the acceptable value was small, therefore it would be necessary to set a reasonable margin when analysis evaluation was to be performed.

Changes in the inner diameter of the body and its strain, which related to the criticality prevention performance, were compared between those obtained from the test and from the analysis. A significant difference was not found in changes in the inner diameter of the body between the results of the test and of the analysis. Strains in the central part of the body in a circumferential direction also showed similar results between the test and the analysis. These results suggested that the analysis could be used to evaluate the ability to maintain the criticality prevention performance.

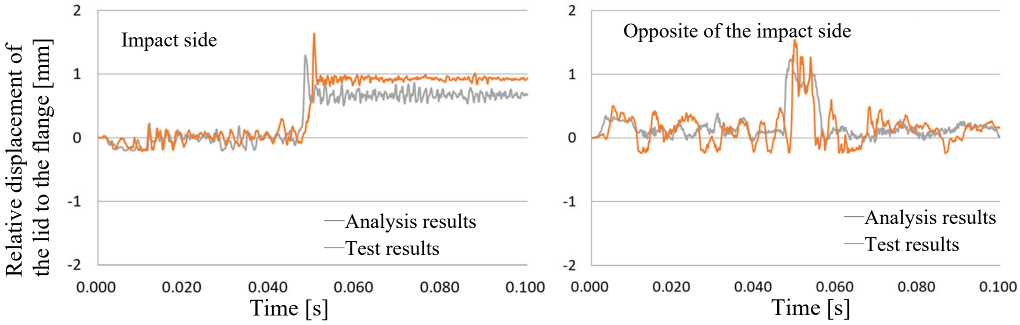


Figure 10 Comparison between the test and the analysis results in the oblique drop test

In the drop of a canister on another canister, the relative displacement of the lid to the flange in an axial direction and the strain of the lid fixing bolts in an axial direction, both related to the confinement performance of the canister, were compared between those obtained from the test and the analysis. The maximum difference in the relative displacement of the lid to the flange in an axial direction was approximately 14% of the acceptable value.

Changes in the inner diameter of the body and its strain, which related to the criticality prevention performance, were compared between those obtained from the test and from the analysis. A significant difference was not found in changes in the inner diameter of the body between the results of the test and of the analysis. Strains in the central part of the body in a circumferential direction also showed similar results between the test and the analysis. These results suggested that the analysis can be used to evaluate the ability to maintain the criticality prevention performance.

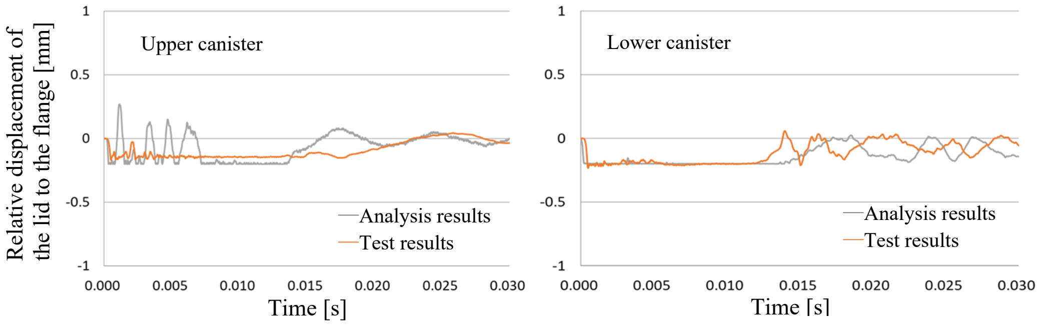


Figure 11 Comparison between the test and the analysis results in the vertical drop test on another canister

(3) Summary of analysis evaluation results

The relative displacement of the lid to the flange, which related to the confinement performance of the canister, was compared between those obtained from the test and the analysis. It was confirmed that the maximum displacements and residual displacements roughly accorded with each other with a difference of 0.6 mm or less. However, it would be necessary to set a reasonable margin for analysis evaluation due to small margins for the acceptable values. Deformation of the inner diameter of the body and its strain, which related to the criticality prevention performance, were compared between the test and the analysis. It was confirmed that both values were roughly accorded with each other, and the analysis could be used for the structural evaluation.

CONCLUSION

The structural integrity of the canister at the assumed drop events has been confirmed by the structural verification tests. In addition, we confirmed the applicability of the structural analysis method by comparing the analysis results with the test results.