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Mechanical test technologies on package for radioactive material transport in CIRP

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Abstract

The container is the unique physical barrier during the transport period, which shall be enough tightness to withstand possible collision scenes. According the requirements of Chinese GB11806 and IAEA's SSR-6, containers for radioactive material transport shall be demonstrated to be enough safety by test or simulation calculation methods. The corresponding mechanical tests items and test requirements are regulated in GB11806 and SSR-6 with regard to the possible collision scenes. By using the approach of combining the test with the finite element simulation for the model 3m^3, model XAYT-I and model ZHQY-QG-001, the application of deformation, stress and acceleration data of key parts of these containers is researched respectively in the safety performance assessment of the containers.

Introduction

The transportation of radioactive material is an essential link of achieving the utilization of nuclear energy and nuclear technology in the industry, agriculture, medicine, scientific research and other fields. The estimated annual shipping volume of packages is more than 30,000,000 pieces in the world. The number of radioactive substance packages transported by railways and roads was 445,000 pieces and 2,130,000 pieces respectively from 1955 to 1985 in China. With the rapid development of nuclear energy and nuclear technology application, the quantity of annual transportation of radioactive substance packages has increased to one million pieces or above [1].

The role of container for radioactive material transport is reflected in two aspects: one is to protect the radioactive material and the other is to protect the environment and the human being from being endangered by the radioactive material. Thus, several important actions are to achieve the effective containment and shielding of the radioactive material , to avoid the criticality. During the transport, the radioactive material are accommodated in the containers and the transport container is the unique protection barrier between the substance and the environment. To achieve the transportation safety mainly relies on the container's ability to withstand the transport environment and possible accidents.

Test requirements

Tests are carried out in accordance with the Chinese national standard "*Regulations for the Safe Transport of Radioactive Material*" （GB11806-2004） [2], which are basically the same "*Regulations for the Safe Transport of Radioactive Material*"（SSR-6,2012 edition）[3,4] of the IAEA on the test and verification technology requirements of the transport packages.

It is required to conduct the free drop test and free drop tests I, II and III, as well as puncture/tear tests of the transport packages for demonstrating ability to withstand drop, impact, penetration and crushing under the normal condition and the accident condition of transport. The tests shall be conducted under the cumulative effect state that may result in the most serious damage to the packages or cause the most serious damage to the packages during the subsequent tests, and therefore, the impact position and impact orientation of the containers shall be taken into consideration. The items and technical requirements of mechanical tests specified for various types of packages are detailed in Table 1 [2,3].

Table 1 Items and technical requirements of mechanical test

Operating Condition	Test Items	Technical Requirements	Package Type
Normal Condition	Free Drop Test	According to the quality of the packages, drop from a height of 0.3-1.2m to the target without deformation. The drop height for the type-A package filled with the liquid and gas is 9m.	A, B, C, fissile material, uranium hexafluoride
Accident	Free Drop Test I	A package drops from a height of 9m to the horizontal target without deformation in the most fragile way.	B, C, fissile material
	Free Drop Test II	A package drops from a height of 1m down to a bar standing firmly on the target, whose diameter is 150mm and length is 200mm.	B, fissile material
	Free Drop Test III	A solid mild steel plate of 1m×1m with a weight of 500kg drops down to the package from a height of 9m in the horizontal state.	B,C, fissile material

Operating Condition	Test Items	Technical Requirements	Package Type
	Puncture/Tear Test	As to the package with a mass less than 250kg, the package on the target shall withstand the impact of a mild steel solid bar with a diameter of 20cm and mass of 250kg dropped from a height of 3m. As to the package with a mass not less than 250kg, the package drops from a height of 3m onto the solid bar (diameter 20cm) of mild steel fixed on the targets	C

Test technology and data analysis

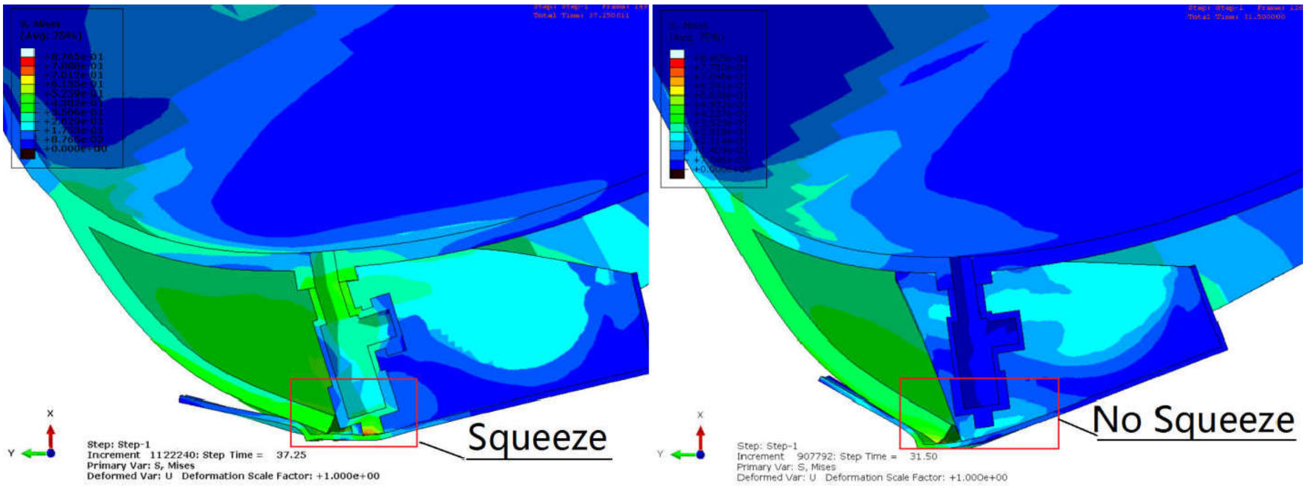
Deformation

The deformation of container is the most intuitive test result. It is also the simplest and the most economic method to measure the deformation of the container. With the method of combining the finite element simulation calculation with the tests, the shielding performance, containment performance and subcritical performance of the container can be judged by researching the parameters of deformation. The deformation size of impacted part of the container can also reflect the energy-absorbing effect of the shock absorbers or parts.

When designing the uranium hexafluoride container of model $3m^3$ with reference the ISO7195, the deformation of skirt base at valve end is studied through the simulation analysis and test in order to prevent the leakage due to the squeeze of valves by the deformation of shirt base and protective cover during the free drop test for a height of 0.6m. The optimized design results show that the deformation of skirt base and protective cover will not squeeze the valve when the thickness of skirt base has reached 22mm, as shown in Table 2, Figure 1 and Figure 2.

Table 2 Calculation results of shell thickness optimization of skirt base at valve end

Thickness of skirt base (mm)	26	24	22	20	16
Whether squeeze the valve	No	No	No	Yes	Yes



(a)16mm (b)22mm

Figure 1 Cloud Picture of maximum impact deformation of skirt base

(a)16mm (b)22mm

Figure 2 End surface to be impacted after free drop tests

Stress

The stress measurement points shall be set up at the key parts or the concerned positions of the container to measure the stress strength during the impact process. Through the comparison with the allowable stress of the material, the safety margin of the material can be judged so as to obtain the assessment results of shielding performance, containment performance and subcritical performance.

Model XAYT-I transport containers was verified under the free drop test I of the accident condition which was designed to transport medical gamma knife therapy head and radiotherapy radioactive sources. The falling posture of container was selected as the apex angle drop (see Figure 3) and the strain gauge was mounted on the external surface of the outer container (see Figure 4 and Table 3) to measure the impact force suffered by the material of outer container. The maximum values of the equivalent stresses σ_r measured at the measuring points 1#, 2# and 3# on the side of outer container are 158.9Mpa, 121.7Mpa and 109.1Mpa, respectively, which are all less than the yield stress ($\sigma_{0.2}$ =205MPa) of stainless steel 0Cr18Ni9. The maximum value of equivalent stress σ_r

measured at the point 4＃ in the center of upper cover is 565.4MPa, which is greater than the yield stress of the material. This indicates a plastic deformation at the measuring point of upper cover, which is consistent with the phenomenon of outward bulge of upper surface of upper cover found after the test.

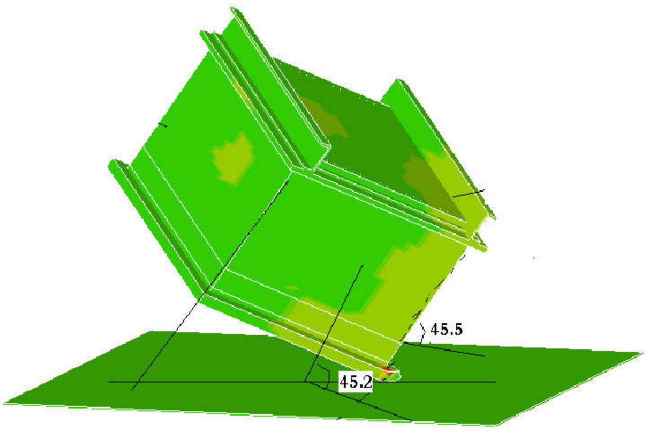


Figure 3 Drop orientation of model XAYT-I container during free drop test I

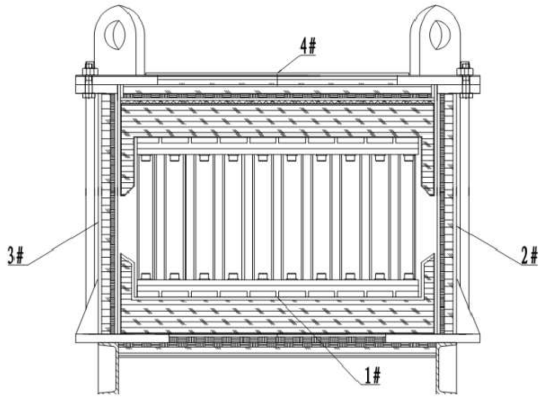


Figure 4 Layout of stress measurement positions

Table 3 Stress measurement positions and maximum values

Point No.	1	2	3	4
Position	center of surface I#	center of surface II#	center of surface III#	center of top surface
Equivalent stress/MPa	158.9	121.7	109.1	565.4

Acceleration

The acceleration data of parts shall be analyzed and measured in the mechanical tests. The stress state and failure mechanism of the parts can be reflected by analyzing the data. Particularly in the design of shock absorbers and among the parts connected by the bolts, it is of a special significance to measure the acceleration data of the parts.

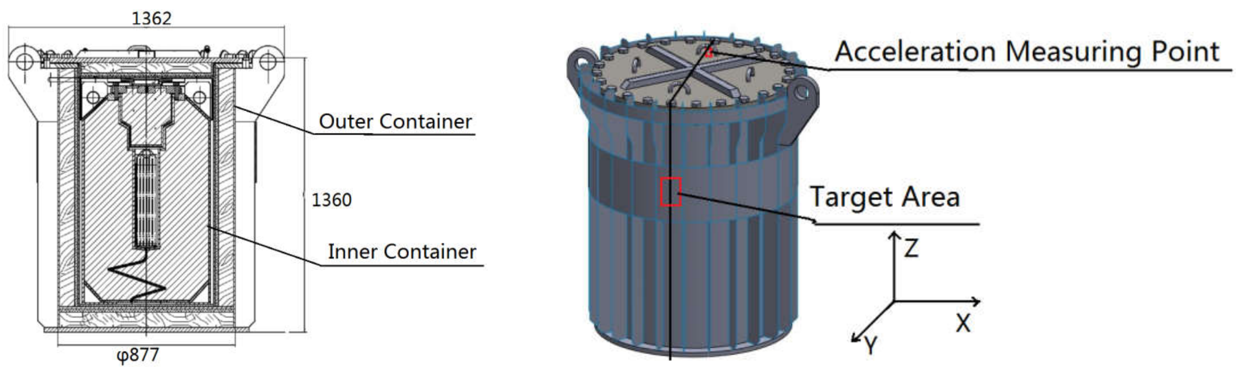


Figure 5 Structure diagram of model ZHQY-QG-001 container and measurement position

In the free drop test II of model ZHQY-QG-001 container used for retired irradiation radioactive sources transport, the position close to the center of outer cylinder wall is taken as the impact position (Figure 5 and Figure 6). The connecting bolts for upper lid and cylinder suffered from impact tension and shear force during the impact process. Using the finite element software Abaqus6.10, the maximum acceleration value (Table 4) of the measuring points of upper lid at 250mm away from edge is measured upon the calculation and test. Through the analysis and comparison of the calculation result from simulation analysis and the actually measured result through the tests, the value obtained from the test is greater than that from the calculation. This mainly demonstrates that the external cylinder wall of outer container has an ability of resisting against the penetration in the free drop test II, and the stiffening ring in the central target area is removed conservatively and the penetration target is directly acted on the external cylinder wall of outer container, which increases the strength of penetration target points and then the impact acceleration in Direction Z and Direction Y.

Table 4 Maximum acceleration values

Direction	X	Y	Z
Calculated Value/g	12.0	20.0	17.5
Measured Value/g	12.7	51.0	36.4

The upper lid of outer container is connected by 24 hexagon head bolts of M30×100 and it is made of 05Cr17Ni4Cu4Nb. The cross section area of threaded portion $A_s=24\times A=24\times 706.5=16956mm^2$. The bolts shall bear the impact force from the inner container, damping ring, disc springs, hanging basket, rubber plate and radioactive source, with a total mass of about 3448kg. The axial tensile strength of the bolts $\sigma=36.4\times 9.81\times 3448\times \sin(25)\div 16956=30.7MPa$. The bolt shall bear the shear impact force of the upper lid of outer container. The mass of upper lid is about 201kg and the radial acceleration is about 52.6g. Thus, the radial shear strength $\sigma=52.6\times 9.81\times 201\div 16956=6.1MPa$. According to the allowable stress limitation of bolts in ASME BPVC-III, the average axial stress is assumed as $0.7S_u=0.7\times 1070=749MPa$ and the shear stress is assumed as $0.42S_u=0.42\times 1070=449.4MPa$. The calculated value and the measured value are all less than the design limit value, so the bolt will not break, and the outer container can protect the inner container.

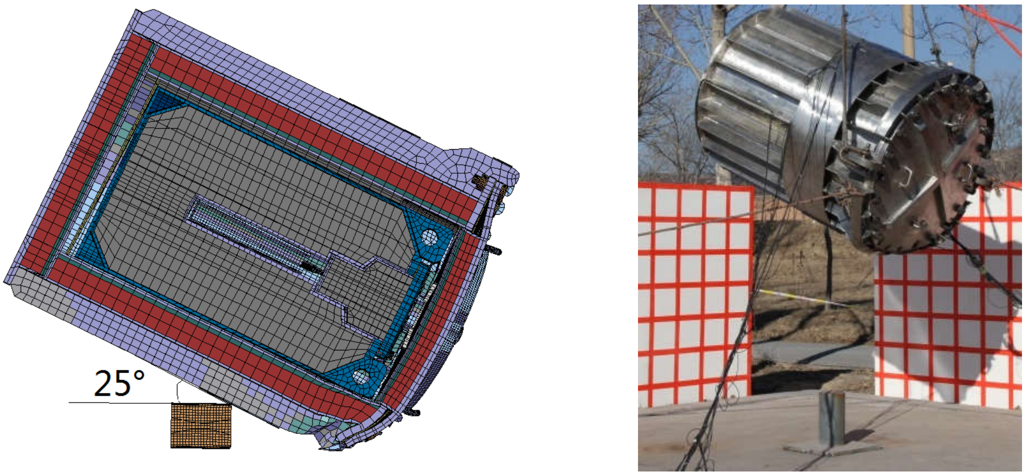


Figure 6 Side puncture test of free drop test II

High-Speed Camera Shooting

The high-speed camera is used to record the collision process of mechanical test of packages. After the test, the analysis to the damage process of the packages can help to understand the mechanism of damage to the packages and improve the design of the packages. Through the analysis of impact process, the impact acceleration and displacement of the packages can be calculated. In order to measure the deformation of the packages, the reference screen shall be used and the signs shall be marked out on the packages. By analyzing the record results of the high-speed camera in combination with the measured results by strain/stress measurement system and acceleration measurement system, the mechanism formed by each peak area in the time-domain diagram of the acquired data can be judged.

Conclusion

The test of packages for radioactive material transport is a destructive test characterized by a wide range of knowledge, a higher technical requirement, a large cost of time and economy and non-repeatability. Therefore, the analysis, tests and measurement technology are very important. It is necessary to try the best to collect the images, stress, acceleration, deformation and other data. By comprehensively analyzing these data, the failure mode of container structure can be obtained so as to improve the design and improve the safety level of the containers.

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