Safety Demonstration Analyses for Severe Accident of Fresh Nuclear Fuel Transport Packages at JAERI

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Abstract

It is expected in the near future that more and more fresh nuclear fuel will be transported in a variety of transport packages to cope with increasing demand from nuclear fuel cycle facilities. Accordingly, safety demonstration analyses of these methods are planned and conducted at JAERI under contract with the Ministry of Economy, Trade and Industry of Japan. These analyses are conducted part of a four year plan from 2001 to 2004 to verify integrity of packaging against leakage of radioactive material in the case of a severe accident envisioned to occur during transportation, for the purpose of gaining public acceptance of such nuclear fuel activities.
In order to create the accident scenarios, actual transportation routes were surveyed, accident or incident records were tracked, international radioactive material transport regulations such as IAEA rules were investigated and, thus, accident conditions leading to mechanical damage and thermal failure were selected for inclusion in the scenario. As a result, the worst-case conditions of run-off-the-road accidents were incorporated, where there is impact against a concrete or asphalt surface. Fire accidents were assumed to occur after collision with a tank truck carrying lots of inflammable material or destruction by fire after collision inside a tunnel.
The impact analyses were performed by using three-dimensional elements according to the general purpose impact analysis code LS-DYNA. Leak-tightness of the package was maintained even in the severe impact accident scenario. In addition, the thermal analyses were performed by using two-dimensional elements according to the general purpose finite element method computer code ABAQUS. As a result of these analyses, the integrity of the inside packaging component was found to be sufficient to maintain a leak-tight state, confirming its safety.

Introduction

Almost all of nuclear fuel materials that are used for nuclear power generation in Japan are imported in the form of UF_6 or UO_2 from foreign countries. Imported nuclear fuel materials are processed into fuel assemblies at a few fuel cycle facilities in Japan.
The transportation of nuclear fuel material in Japan is mainly over land, by truck. Enriched UF_6 is transported from a port or enrichment facility to a reconversion facility, and then the UO_2 powder is transported from a port or reconversion facility to a fuel fabrication facility. Finally, the fuel bundles are transported from fuel fabrication facility to nuclear power plants. The distance of transportation depends on the location of ports, fuel cycle facilities, and nuclear power plants. We selected some transport packages to evaluate their safety under realistic severe accident conditions, for the purpose of demonstrating the safety of radioactive material transported in Japan. This was done under contract with Ministry of Economy, Trade and Industry in Japan for the purpose of gaining public acceptance (P.A.) of such nuclear fuel activities.
This report provides an outline of the severe accident scenario utilized, and the impact analysis and thermal analysis results of the 1) enriched UF_6 transport package and 2) UO_2 powder transport package.

Confirmation of the transport route

The actual transportation routes are not disclosed in order to protect the nuclear material. However, we think that it is rational in view of transport efficiency to suppose the route to be as follows.
1) The package shall be transported mainly utilizing expressways.

2) The section of public road that is used in the transport of nuclear fuel material is only that between the nearest expressway off ramp / on ramp and the port, nuclear fuel cycle facility or nuclear power plant.
The expressway was selected for evaluation of severe accident in nuclear fuel material transport. The characteristics of the expressway in Japan are 1) 2 lanes on one side, 2) one-way, 3) speed limit is 100 km/h.
In transport of nuclear materials, one or more trucks loaded with such nuclear fuel materials travel in a line with accompanying cars and security guard cars in front of and behind the trucks.

Determination of the accident scenario

We investigated the accident environment in expressways for not only a nuclear material transport vehicle but also all vehicle. We created a scenario of a severe accident during nuclear material transportation as follows.

Accident scenario where mechanical damage to package

As a result of investigation, the main possible features of such accident situations were found to be as follows.
1) Multi-vehicle collision,
2) Package dropped from an elevated road.
3) Package tip-over onto the road or tip-over after a collision
4) Fire by collision in or out of a tunnel

The main causes of the above accident situations were 1) sudden steering maneuvers, 2) speeding. The probability of such accidents occurring during nuclear material transportation with a line of trucks is very small. As actual accident during nuclear material transportation was reported in NUREG/CR-4829. We have made the severe mechanical impact accident scenario for safety evaluation a fall from an elevated road to concrete or asphalt pavement.

Accident scenario where thermal damage to package

The following are reported for the fire accident.
1) Fire, after the collision with an other vehicle in opening space
2) Fire, after multi-vehicle collision
3) Fire, caused by collision with a tank truck
4) Fire after collision with an other vehicle in a tunnel
5) Large-scale fire in a tunnel

The severeness of the fire accident depends largely on the fire fighting activity of the fire department. We assumed that the severest fire is a fire with a large quantity of combustible fuel or where fire fighting activity is not easy to carry out.
We have made the severe fire accident scenarios for safety evaluation a fire caused by the collision with a tank truck and fire after the collision with an other vehicle in a tunnel.
Furthermore, either mechanical or heat damage is conceivable in a fire accident. However, the mechanical damage was slight in the fire accident case that we investigated. Therefore, damage only by heat of the fire is considered in this report.
The duration of the fire caused by collision with a tank truck was estimated from the actual accident case in a foreign country and from combustion test results. The estimate of duration of fire in the tunnel was based on an actual accident case. The ventilation speed inside the tunnel was set to be 0.2m/s, the minimum oxygen supply quantity necessary to continue burnup. The energy of inflammable materials at the time of the fire was set to be 38.7GJ in consideration of the fuel, vehicle main body and also material loaded in accident vehicles. The burnup pattern was set up referring to an example of a fire in a bus that broke out in a tunnel

Safety evaluation of UO_2 powder transport package

The conventional UO_2 powder transport packaging was a metal barrel style transport packaging such as BU-J. After 2000, the box style transport packaging was developed in order to improve transport efficiency. Approval and license for this package was acquired and it has been in practical use. We selected a box style UO_2 powder transport packaging as the object of the evaluation of safety, considering that this packaging will be the mainstream from now on.[1]

Drop Impact analysis

Setting of the impact surface

The concrete and asphalt pavement that will be the impact surface were modeled with three-dimensional solid elements considering the nature of the roadbed, path of fall etc, in the light of the examination results of Akamatsu[2]. The concrete and asphalt were set up giving the conditions where deformation ruptures or does not rapture the surface. The no-bounce-back condition was set up in the boundaries of the model of the impact surface.

Analysis model

The analysis code LS-DYNA3D (Ver960) was used. The main body and lid of an Outer Confinement Assembly and nine Inner Containment Canister Assemblies were modeled as shell elements. The thermal and impact protection materials were modeled as solid elements.

Impact attitude

Impact at the corner of Outer Confinement Assembly lid and the side edge of Outer Confinement Assembly was modeled, since this is the severest impact attitude for the box type UO_2 powder transport packaging. The basic impact at the corner of Outer Confinement Assembly is shown in Figure 1.

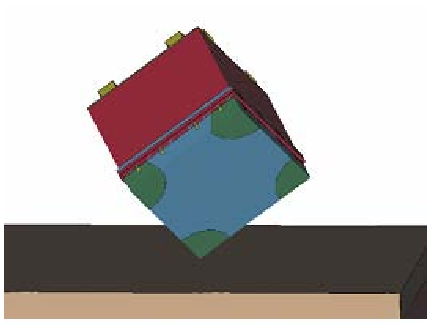

Fig.1 FEM model of UO_2 powder transport package impact at the corner

The analysis result

The analysis result of impact at the corner of Outer Confinement Assembly lid is shown in Figures 2 and 3. Results of analysis showed that the highest effective plastic strain was 25.8% in the Inner Containment Canister Assembly closest to the impacting face. This value was below that causing rupture deformation of the material.

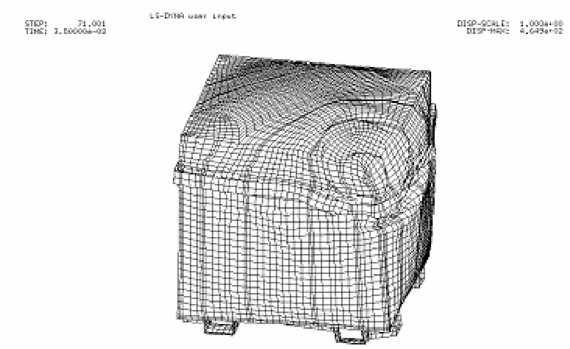

Fig.2 Analysis result of impact at the corner

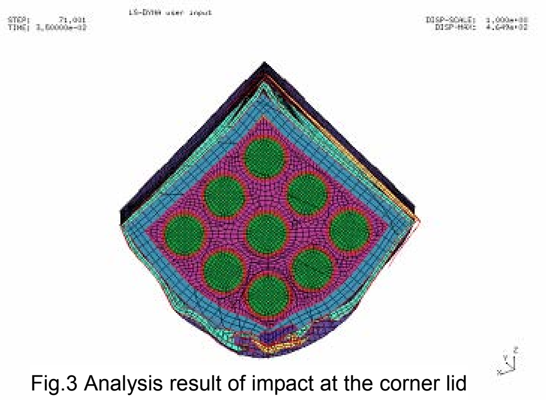

Fig.3 Analysis result of impact at the corner lid section view

Therefore, the Inner Containment Canister Assembly did not rupture even at the time of impact accident. Thus, the confinement safety of the UO_2 powder that was stored was secured. The neutron moderator/absorption material that was located in the Inner Containment Canister Assembly body kept its specified position without dropping out from the Inner Containment Canister Assembly. The interval between the Inner Containment Canister Assemblies approached 48 mm at the internal closest to the impacting face. The range of change in the neutron multiplication factor due to the change of interval between Inner Containment Canister Assemblies was small. Thus, the criticality safety is secured.

Thermal safety analysis

Fire, caused by collision with a tank truck

Analysis model

ABAQUS6.2, a finite element analysis code, was used. The box type UO_2 powder transport packaging was modeled with two-dimensional elements. Element division is shown in Figure 4. The maximum temperature inside the transport package is evaluated by the following analysis procedure.

1) Analysis of the initial component temperatures. The temperature of the package is calculated until it reaches thermal equilibrium with an ambient temperature of 38°C and insolation.
2) Analysis during the thermal event of a severe accident.
3) Analysis during the cool-down period following a severe accident. The temperature of the package is calculated for an ambient temperature environment of 38°C and insolation.

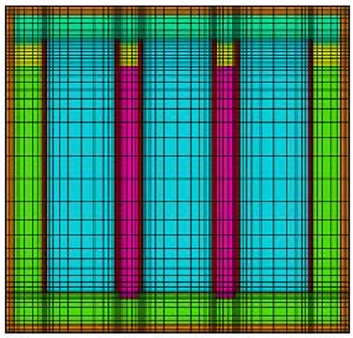

Fig.4 thermal analysis FEM model of UO_2 powder transport package

The analysis result

The analysis result of temperature distribution in the box type UO_2 powder transport package is shown in Figure 5. The analysis result of temperature history inside of the box type UO_2 powder transport package is shown in Figure 6. The maximum temperature becomes 110°C inside the transport package and thus does not exceed the use limit temperature.

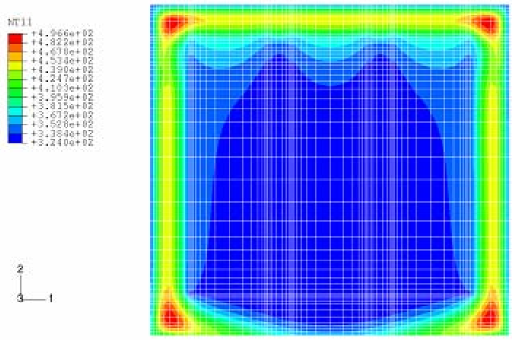

Fig.5 Analysis result of temperature distribution in the UO_2 powder transport package

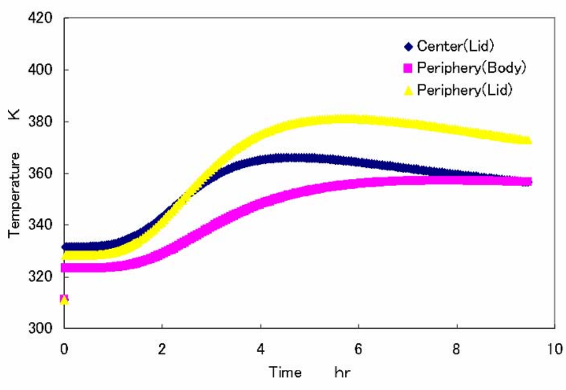

Fig.6 Analysis result of temperature history inside of the UO_2 powder transport package

Fire after collision with an other vehicle in the tunnel

The analysis model of the whole tunnel is shown in Figure 7. The size of the tunnel is 10 m (Wide)×5 m (Height) and the length was made 120 m. The analysis model of transport package was same as in Figure 4. The maximum temperature inside the transport package is evaluated by the following analysis procedure.

1) Analysis of the initial component temperatures.
2) Analysis during the thermal event of a severe accident. Temperature history of the surface of transport package at the time of the fire and cool-down was analyzed by using the whole tunnel model
3) The above temperature history was given to the transport package model as a boundary condition. The temperature history inside the transport package was analyzed.

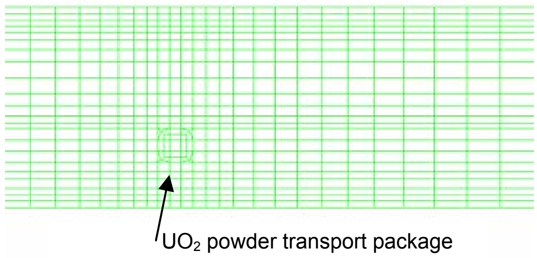

Fig.7 analysis model of the whole tunnel

The temperature distribution of the heat fluid within the tunnel 2 hours after fire extinguishment is shown in Figure 8. The maximum temperature of the heat fluid within the tunnel 10 minutes after the start of the fire was 1101°C (1374K). Further, the maximum temperature of the heat fluid within the tunnel at the time of fire extinguishment was 471°C (747K). Flame compartments showed uniform temperature, and the heat fluid moved by ventilation. There was a cooling delay after fire extinguishment at the ceiling, way road, and lower stream of transport package. The temperature distribution within the transport package 10 minutes after the start of the fire is shown in Figure 9. Although the maximum temperature was reached at the surface of the transport package at this time, the temperature rise inside the transport package was small. The temperature rise inside the transport package was also small during the fire extinguishment.

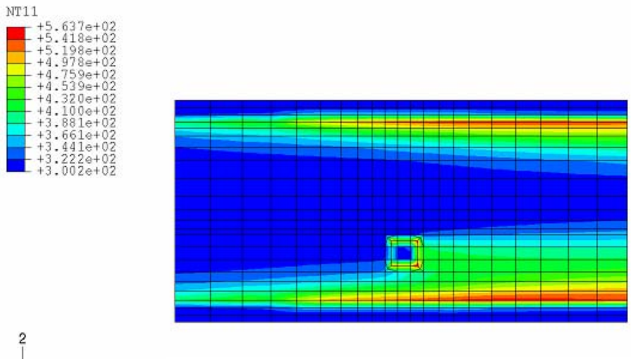

Fig.8 temperature distribution of the heat fluid within the tunnel 2 hours after fire extinguishment

6 hours after fire extinguishment, the inside temperature of transport package became the

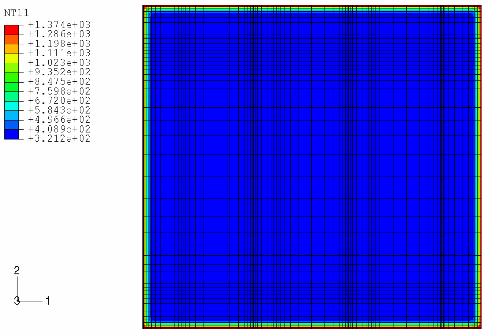

Fig.9 temperature distribution within the transport package 10 minutes after the start of the fire

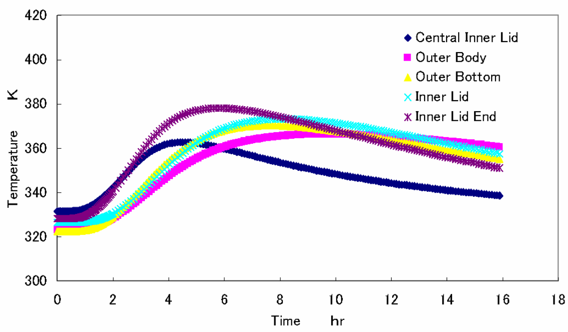

Fig.10 Analysis result of temperature history inside of the UO_2 powder transport package

maximum. This is because the temperature inside the transport package became uniform by heat conduction. The temperature histories of Inner Containment Canister Assemblies are shown in Figure 10. The highest attained temperature was about 105°C (378K).
The highest attained temperature of the Inner Containment Canister Assembly was below the use upper limit temperature of an Inner Containment Canister Assembly lid gasket and that of a neutron moderator/absorption material. It was confirmed that the confinement function of the storage is maintained because the soundness of the gasket was maintained. It was confirmed that the subcritical state is secured because the functional soundness of the neutron moderator/absorption material was maintained against heat.

Safety evaluation of enriched UF_6 transport package

Usually, overpack and a 30B cylinder with a valve protection device (VPD) containing enriched UF_6 are used for shipment. Recently, a new design of overpack with no VPD was developed and approved by competent authorities. We evaluated the safety of an enriched UF_6 transport packaging with no VPD[3].

Drop Impact analysis

Analysis model

Analysis code LS-DYNA3D (Ver960) was used. The transport package is shown in Figure 11. The overpack consists of an outer shell, inner shell, and shock absorbing and/or fire resistant material. The 30B cylinder has a valve and plug. The shock absorbing and/or fire resistant materials were modeled with one point integrated solid element. Other materials in the structure were modeled as one point integrated shell elements. The upper part and lower part of the overpack were modeled that rigidly tightens by the fastening device. The valve were approximated with a hexagon pillar in accordance with its external form, and modeled as a rigid body.

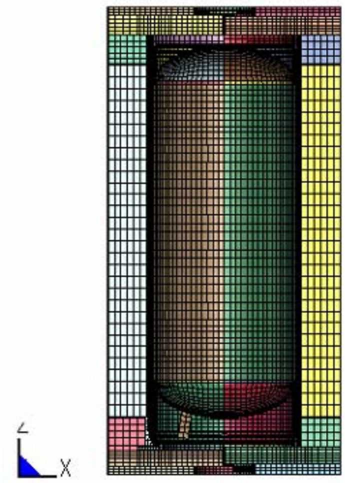

Fig.11 FEM model of UF_6 transport package for drop impact analysis

Impact attitude

Impact at the corner (valve side), in a vertical attitude, and in a horizontal attitude were modeled, these being the severest impact attitudes for the enriched UF_6 transport package.

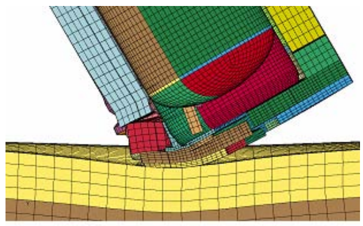

Fig.12 condition of the deformation in the valve vicinity at the time of impact at the corner

The analysis result

The condition of the deformation in the valve vicinity at the time of impact at the corner is shown in Figure 12. The time history of the distance between the valve and inner shell is shown in Figure 13.
The valve did not contact with any other structures, such as the inner shells, in any of the impact attitudes. The minimum distance between the valve and inner shell was 47 mm. On the other hand, the maximum effective plastic strain on the 30B cylinder was 1.6%, which is below the rupture value.

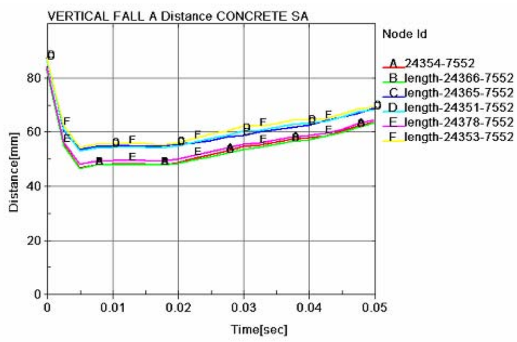

Fig.13 time history of the distance between the valve and inner shell

Thermal safety analysis

Fire, caused by collision with a tank truck

Analysis model

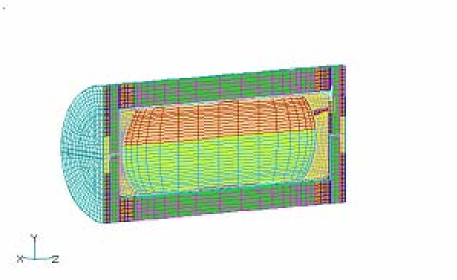

Fig.14 FEM model of UF_6 transport package for thermal safety analysis

In consideration of the points below characterizing the transport package, in constructing the three-dimensional structure consisting of an overpack and 30B cylinder, we used the model as shown in Figure 14. ABAQUS6.2, a finite element analysis code, was used.

- Because of the symmetry of the vertical section of transport package along the axial direction, the analysis model was made 1/2 of the package, cut along the axis.
- The valve was modeled as a cylinder form solid element. The plug was modeled as a shell element.
- The enriched UF_6 that is a storage material was filled in the 30B cylinder to the normal weight.

Thermal radiation, convection and solar radiation heat between the overpack outer shell and outside environment were considered. Radiation and convection between the overpack inner shell and surface of the 30B cylinder were considered.

The analysis result

The temperature distribution 90 minutes after the start of the fire is shown in Figure 15. The highest attained temperature was 89.2°C, well below the limiting temperature, and the pressure was below the resisting pressure limit of 30B cylinder.
The volume of the contained UF_6 was 63.9% of inside capacity of the 30B cylinder under normal conditions and 66.1% of inside capacity of the 30B cylinder at the time of fire extinguishment. The inside of the 30B cylinder was not filled with liquid.
The history of temperature at valve and plug top that are a sealing boundaries, are shown in Figure 16. The highest attained temperature was 92.7°C at the valve and 65.8°C at the plug. These temperatures did not exceed the melting point of the solder.

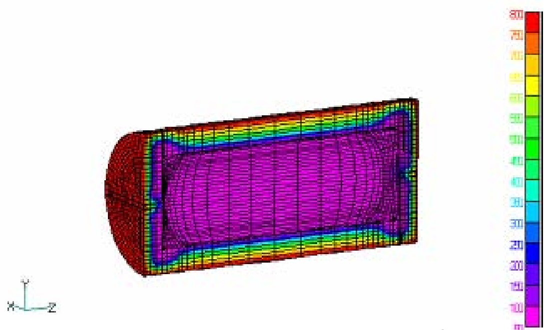

Fig.15 temperature distribution 90 minutes after the start of the fire

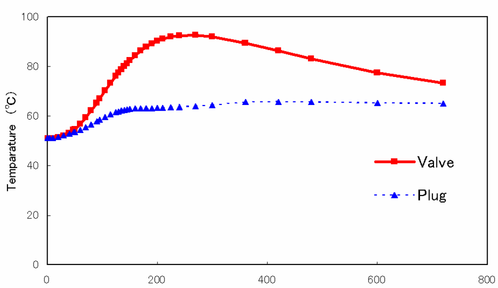

Fig.16 history of temperature at valve and plug

Fire after collision with an other vehicle in the tunnel

The temperature of the stationary state of the transport package exposed to solar radiation was

54.6°C. This value was input to the transport package part of the whole tunnel model. The temperature distribution of the heat fluid within the tunnel 10 minutes after the start of the fire is shown in Figure 17. The maximum temperature of the heat fluid within the tunnel in this time was 1140°C (1413.6K). The maximum temperature of the heat fluid within the tunnel at the time of fire extinguishment was 162.5°C (435.6K). The maximum temperature of outer surface of transport packaging 10 minutes after the start of the fire was 899°C.

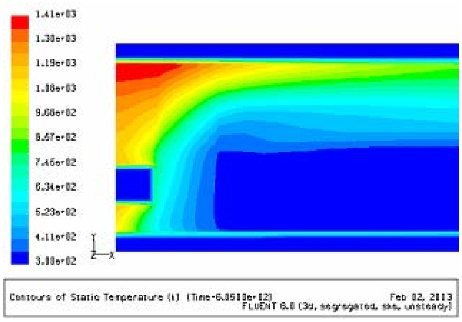

Fig.17 temperature distribution of the heat fluid within the tunnel 10 minutes after the start of the fire

We evaluated the inside temperature of the transport package of case at the time of the tunnel fire on the basis of the aforementioned result. The temperature distribution inside the transport package 10 minutes after the start of the fire, the time when the heat fluid inside the tunnel is the highest temperature, is shown in Figure 18. Although the outer surface of the transport packaging comes to have a high temperature, the temperature rise inside the package was small. The temperature of the transport package surface becomes the highest 120 minutes after, the start of the fire, 141°C.

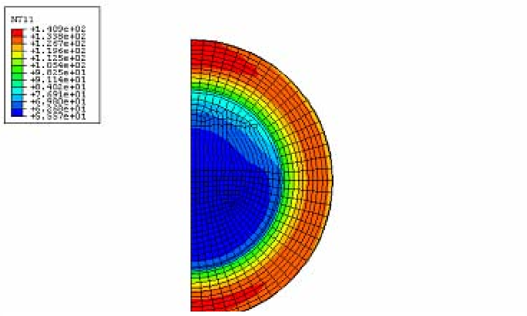

Fig.18 temperature distribution inside the transport package 10 minutes after the start of the fire

The temperature history of the UF_6 and 30B cylinder is shown in Figure 19. The highest attained temperature of the 30B cylinder was 84.0°C, and that of UF_6 was 66.8°C.

The volume of the contained UF_6 was 64.1% of the inside capacity of the 30B cylinder at the time of the above stationary state and 65.1% of inside capacity of the 30B cylinder at the time of fire extinguishment. The inside of the 30B cylinder was not filled with liquid.

Conclusion

As a result of evaluation of envisioned severe accident scenarios, it is predicted that the UO_2 powder transport package and the enriched UF_6 transport package will not receive such impact damage at the time of drop impact that there are ill effects on the confinement and criticality of radioactive materials.

The UO_2 powder transport package and the enriched UF_6 transport package also do not receive such heat damage that there are ill effects on the confinement and criticality of radioactive materials at the time of an engulfing fire.

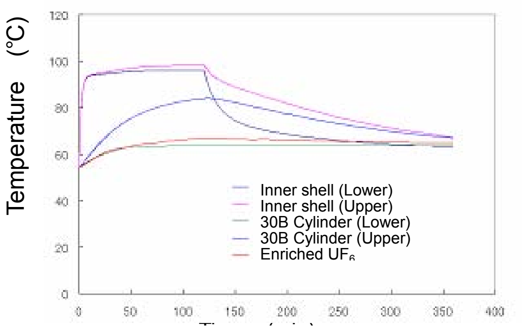

Fig.19 temperature history of the UF_6 and 30B cylinder

Reference

[1] Docket 71-9294 Rev. 2 'GNF NPC Safety Analysis Report', 1/2001

[2] H.Akamatsu et al. “Behaviour of a Package Dropped onto Yielding and Unyielding Targets” RAMTRAMS Vol8, Nos 3-4, pp. 293-297 (1997)

[3] Docket 71-3057 Rev. 1 'Safety Analysis Report for the Model MST-30 protective shipping package for 30-inch UF_6 cylinders', 9/2001