# DEMONSTRATIVE RUPTURE TEST AND SAFETY EVALUATION OF A NATURAL $UF_6$ TRANSPORT CYLINDER AT HIGH TEMPERATURE

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## ABSTRACT

If the natural Uranium hexafluoride ($UF_6$) transport container is involved in a fire test condition as described in the new requirements from the International Atomic Energy Agency (IAEA), packaged $UF_6$ can easily be transformed from solid phase to liquid or gas phase at a comparatively low temperature, and can cause an inner pressure increase. Therefore, it is very important to evaluate the thermal-mechanical characteristics of $UF_6$ transport container under realistic fire conditions. Rupture tests with the 48Y-cylinders were performed in the joint research works (PEEHCEURE Program) between Central Research Institute of Electric Power Industry (CRIEPI, Japan) and Nuclear Protection and Safety Institute (IPSN, France) [1]. This type of cylinder seems to be deformed and ruptured near the stiffener ring due to creep deformation.

A series of material tests on small-scale specimens of the container material were performed to propose creep deformation formula and a rupture criterion. To assess the rupture possibility of the container, this proposed non-linear creep material model was applied to the ABAQUS code and the numerical analysis was performed and compared with the rupture test results. Finally, according to the thermal-mechanical analysis for 48Y-clinders with the Japanese heat protect system, it can be concluded that this natural $UF_6$ transport system has enough safety margin for the new IAEA fire test requirement.

## INTRODUCTION

$UF_6$, the raw material from which the fuel for nuclear power stations is obtained, is stored and transported in solid state in industrial containers called 48Y-cylinder. In 1996, IAEA revised the transport regulation for natural $UF_6$ transportation taking into account chemical and radiological hazards. A new fire test requirement (engulfing fuel fire of 800$^{o}$C for half an hour, for a steel emissivity of 0.8 and flame emissivity of 0.9) was imposed on this type of container. When the $UF_6$ transport container is involved in a fire, packaged $UF_6$ can easily be transformed from solid phase to liquid or gas phase at a comparatively low temperature, and can cause an inner pressure increase. The structural strength of the cylinder material (ASTM SA516 carbon steel for moderate and low temperature service) also decreases with increasing temperature [2]. Therefore, it is very important to evaluate the thermal-mechanical behavior of $UF_6$ cylinder under realistic fire conditions, especially the possibility of rupture of the cylinder.

## THERMAL-HYDRAULIC ANALYSIS FOR IAEA REGULATION

The $UF_6$ is a colorless solid at ambient temperature. The specific characteristics of the thermal behavior of $UF_6$ are its low temperature triple point (0.15MPa, 64 $^{o}$C), phase change and volume expansion. If the fire test is imposed on the 48Y-cylinder, a very complicated heat transfer including boiling phenomena as shown in Fig.1 takes place. Commissariat A l'Energie Atomique (CEA) carried out several thermal-hydraulic numerical analyses and interpretations of physical phenomena of the 48Y-cylinder under the new fire test condition from the IAEA regulation revised in 1996 with the

DIBONA-2D computer code [3]. This code was developed according to the acknowledgements obtained in the experimental joint research works (TENERIFE Program) performed by CRIEPI and IPSN from 1991 to 1996 [4], and can consider the specific physical phenomena as shown in Fig.1, such as expansion due to the density difference between solid and liquid $UF_6$, heat transfer during boiling, condensation of the vapor bubbles, equation of state of $UF_6$ and melting and sinking of solid. Fig.2 shows an example of the numerical results. It seems that a very complicated heat transfer including boiling phenomena will take place and lead to a rapid increase in pressure in the last ten minutes of the fire test.

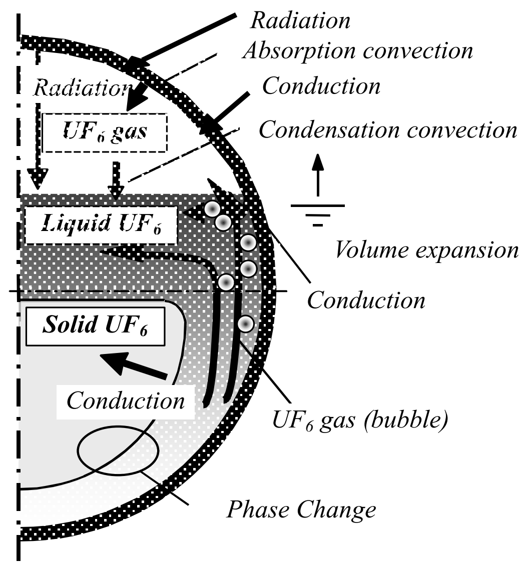



Fig.1 Diagram of Heat Transfer in the Cylinder

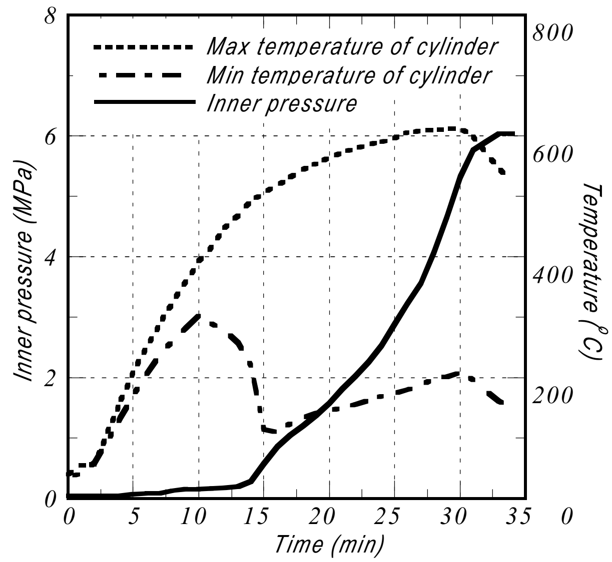



Fig.2 Fire Test Analysis Results

**DEMNSTRATIVE RUPTURE TEST WITH FULL-SCALE 48Y-CYLINDER**

According to the thermal-hydraulic numerical analysis results with the DIBONA-2D computer code under the fire test condition described in the IAEA regulation, it seems that a very complicated heat transfer including boiling phenomena will take place and lead to a rapid increase in pressure in the last ten minutes of the fire test. The ASME SA516 carbon steel for moderate and lower temperature service is now used as the structural material for natural $UF_6$ container. The structural strength of the container material decreases with increasing temperature. Therefore, it is very important to assess the safety of natural $UF_6$ transport container under realistic fire conditions, especially rupture possibility of the container due to the rapid increase in pressure.

**PEECHEUR Program**

In PEEHCEURE Program, three rupture tests with the full-scale 48Y-cylinders of different grades were performed to evaluate the mechanical characteristics under high pressure and at high temperature. Table1 and Fig.3 shows the rupture test parameters and conditions. In each test, test containers were heated after being previously equipped and insulated, and pressurized of nitrogen until rupture took place. For test A and B, to simulate the extended regulatory fire test of the IAEA, a temperature distribution and a rate of pressure rise with respect to time were controlled in the same range as the calculated results by DIBONA code. In these tests, the test containers were filled to 80% volume with dry sand. For test C, to confirm the rupture characteristics at a lower speed with no thermal gradient, the empty container was uniformly heated and the internal pressure was gradually increased.

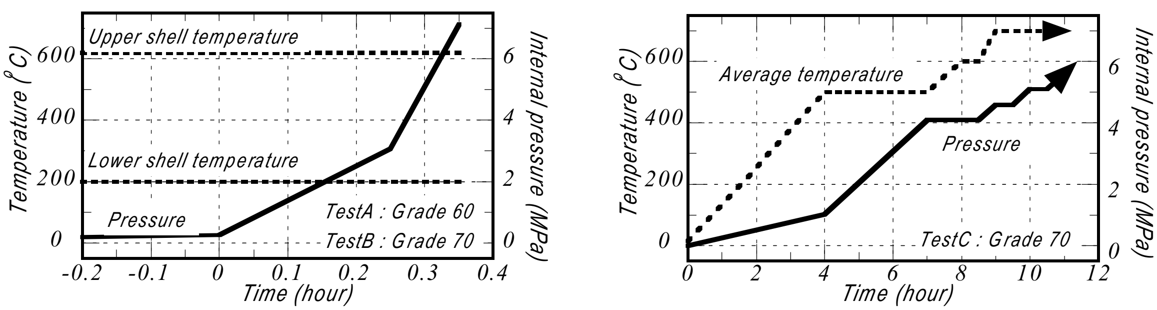
**Rupture Test Results**

Fig.4 shows the schematic of the test containers after the tests. According to these test results, this type of cylinder seems to be deformed and ruptured near the stiffener ring due to creep deformation. In the test A, rupture occurred at a pressure of 52bar. Large deformations had taken place on the upper shell and the stiffener had ruptured at the butt-weld, causing the shell to tear in a longitudinal direction. The width of the opening was 4cm at the base of the stiffener and 7cm at its end, the length of the tear being approximately 20cm.

Table1 Rupture test parameters

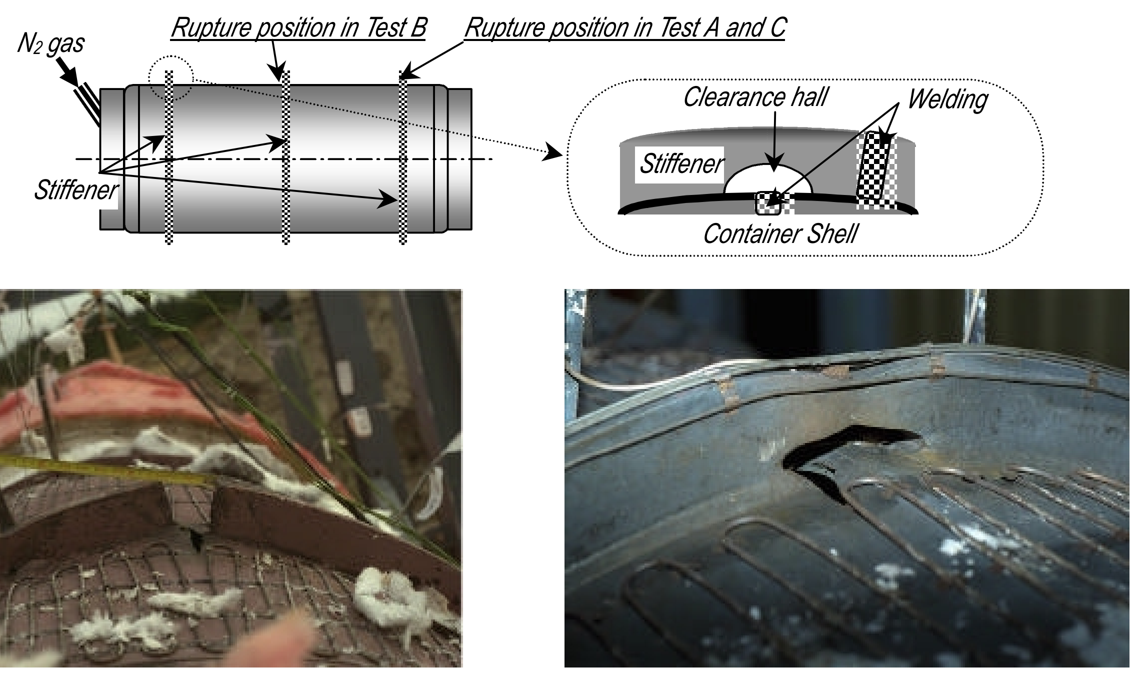
| Test | Material | Contents | Temperature | $P_{rupture}$ | Ruptured position |
|---|---|---|---|---|---|
| A | Gr.60 | Dry sand | Lower surface : 200$^o$C | 52bar | Stiffener root at butt-weld |
| B* | Gr.70 | | Upper surface : 620$^o$C max. | 53bar | Stiffener root at clearance hole |
| C | Gr.70 | Empty | Constant temperature at 620$^o$C | 40bar | Stiffener root at butt-weld |

* Butt-Welds of the stiffeners were inspected by radiation technique and repaired.




(Test A and B) (Test C)

Fig.3 Rupture test conditions




(Test A) (Test B)

Fig.4 Test container after rupture test

## MATERIAL TEST

As ASME SA516 steel is not generally used for high temperature work material characteristics had not been available above 500 $^{o}$C. Tensile tests and creep tests with this material were executed under high temperature and at high stress condition, and the creep deformation formula and creep rupture criteria were proposed.

### High Temperature Tensile Test

Tensile tests from room temperature up to 900 $^{o}$C were conducted using several base metal and seam-welded joints of SA516 [2]. The strain rate of the test was $5x10^{-3}min^{-1}$ and over 0.2% proof stress was $6x10^{-2}$ $min^{-1}$. Fig.5 shows an example of the test results. The tensile strength values and 0.2% proof stress decrease with increasing temperature. On the other hand, the values of the reduction area and elongation increase with increasing temperature. The position of rupture of seam-welded joints was the base metal at temperatures from room temperature up to 800 $^{o}$C, but at 900 $^{o}$C, the rupture position was the weld metal.

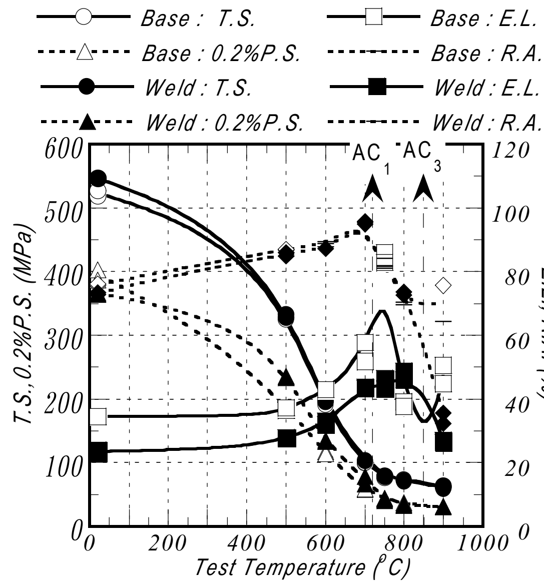


Fig.5 Tensile Properties of SA516 steel (Grade 65)

### Creep Deformation Properties

Short-time uni-axial creep tests and interior pressure creep tests using cylindrical test pieces were conducted at 600-900$^{o}$C and at various stress levels at each temperature (stress range:8-45MPa) by using SA516 Gr.65 base metal, and the creep constitutive equation had been proposed especially paying attention to the high temperature service region beyond 700$^{o}$C [2]. To extrapolate the creep deformation in lower temperature service region with high stress condition, additional creep tests were conducted at 550-700$^{o}$C and at various stress levels at each temperature (stress range:15-60MPa) and modified creep deformation formula are proposed as follows.

$$\varepsilon_C = \varepsilon_T + \dot{\varepsilon}_S\, t \qquad (1)$$

$$\varepsilon_T = \varepsilon_T^S \left[ 1 - exp\left\{ -1.723\left( \dot{\varepsilon}_S\, t \right)^{0.528} \right\} \right] \qquad (2)$$

$$\varepsilon_T^S = exp(0.0592\bar{\sigma})\, exp\left( -\frac{5060}{T+273} + 1.21 \right) \qquad (3)$$

$$\dot{\varepsilon}_S = 7.262\times 10^{12}\, exp\left(0.339\bar{\sigma}\right) exp\left( -\frac{2.063\times 10^{2}\,\bar{\sigma} + 3.321\times 10^{4}}{T+273} \right), \quad T < 723°C$$
$$\dot{\varepsilon}_S = 5.124\times 10^{9}\, exp\left(-0.641\bar{\sigma}\right) exp\left( \frac{2.266\times 10^{2}\,\bar{\sigma} - 2.668\times 10^{4}}{T+273} \right), \quad 723°C < T < 845°C \qquad (4)$$

where, $\varepsilon_c$ :creep strain (%), $\varepsilon_T$ :transition creep strain (%), $\varepsilon_T^S$ :saturated transition creep strain (%), $\dot{\varepsilon}_s$ :minimum creep strain rate (%/hour), $t$ :time(hour), $\bar{\sigma}$ : Mises stress (MPa), $T$ :test temperature ($^{o}$C)

Fig.6 shows the modified relationship between the test temperature and calculated minimum creep strain rate with the experimental values.

### Creep Rupture Criteria

Interior pressure creep rupture tests using cylindrical test pieces were also conducted at 600-800 $^{o}$C and at various stress levels at each temperature (Mises stress range: 30-140MPa) using SA516 Gr.65 base metal, and the life-time formula had been also proposed especially paying attention to the high temperature service region beyond 700$^{o}$C [2]. To estimate the lifetime adequately in lower temperature service region with high stress condition, additional creep rupture tests were conducted at 550-700 $^{o}$C and at various stress levels (stress range:40-140MPa) and modified life-time formulae is proposed based on the Goldhoff-Sherby parameter method as follows.

$$\log t_r = \left( \frac{1}{T + 273} - 0.00139 \right) \cdot \left( \frac{\bar{\sigma} + 63.26}{0.00651} \right) + 6.507 \quad (5)$$

where, $t_r$: rupture time (h)

Fig.7 shows the modified relationship between the Mises stress and rupture time. To evaluate the possibility of rupture of the 48Y-cylinder, according to the modified life-time formula represented by equation (5), the rupture time was estimated by Robinson's law method. In this method, the rupture is assumed to occur when the sum of the creep damage factor exceeds the threshold value $f_s$ as follows.

$$D_C = f_S \cdot \sum (t_i / t_{ri}) \quad (6)$$

where, $D_c$: creep damage factor, $t_i$: time at certain constant condition, $t_{ri}$: rupture time calculated by equation (5), $f_s$ :safety factor

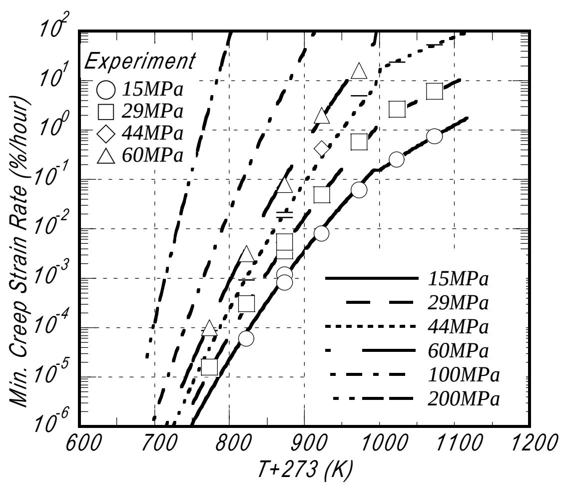



Fig.6 Modified Relationship between Test Temperature and Min. Creep Strain Rate

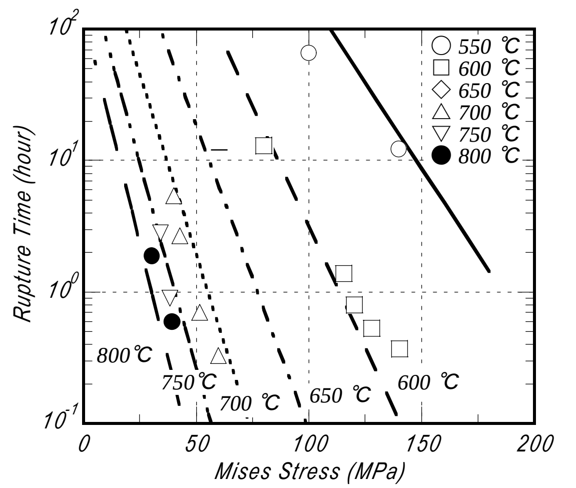



Fig.7 Modified Relationship between Mises Stress and Rupture Time

Table2 Determination of Safety Factor $f_s$ for Creep Damage Factor

| Case | Temperature | Applied step-stress | Step time | Specimen | $D_c$ |
|---|---|---|---|---|---|
| 1 | 700$^{o}$C | from 40 to 50 MPa | 1.50 hr. | Base metal | 0.38 |
| 2 | | from 50 to 60 MPa | 0.40 hr. | | 0.28 |
| 3 | 600$^{o}$C | from 115 to 130 MPa | 0.70 hr. | | 2.40 |
| 4 | | from 125 to 140 MPa | 0.27 hr. | | 1.74 |
| 5 | 700$^{o}$C | from 40 to 50 MPa | 1.50 hr. | Welded | 0.79 |
| 6 | | from 50 to 60 MPa | 0.40 hr. | | 0.72 |
| 7 | 600$^{o}$C | from 115 to 130 MPa. | 0.70 hr. | | 3.28 |
| 8 | | from 125 to 140 MPa | 0.27 hr. | | 4.99 |

To determine the safety factor of creep damage $f_s$, creep rupture tests under varying stress conditions as shown in Table2. As the minimum value of $D_c$ was 0.28, the safety factor of creep damage $f_s$ was set to 0.25 for the conservative estimation of rupture time.

## THERMAL-MECHANICAL BEHAVIOR OF $UF_6$ CYLINDER

### Verification Analysis for Rupture Test

Modified non-linear creep material model described above was applied to the ABAQUS computer code, and the three-dimensional numerical analysis was executed for the rupture tests performed by the PECHEEUR Program to verify this material model. Fig.8 shows the analysis results for rupture test A. It was found that considerable creep deformations are generated and the creep damage factor exceeds the proposed threshold value under the inner pressure between 4 and 5 MPa. As this finding is in good agreement with the bursting conditions obtained by the rupture test, it seems that the evaluation method proposed in this study will be sufficiently applicable to the safety analysis of transport of 48Y-cylinder subjected to high temperature and high pressure.

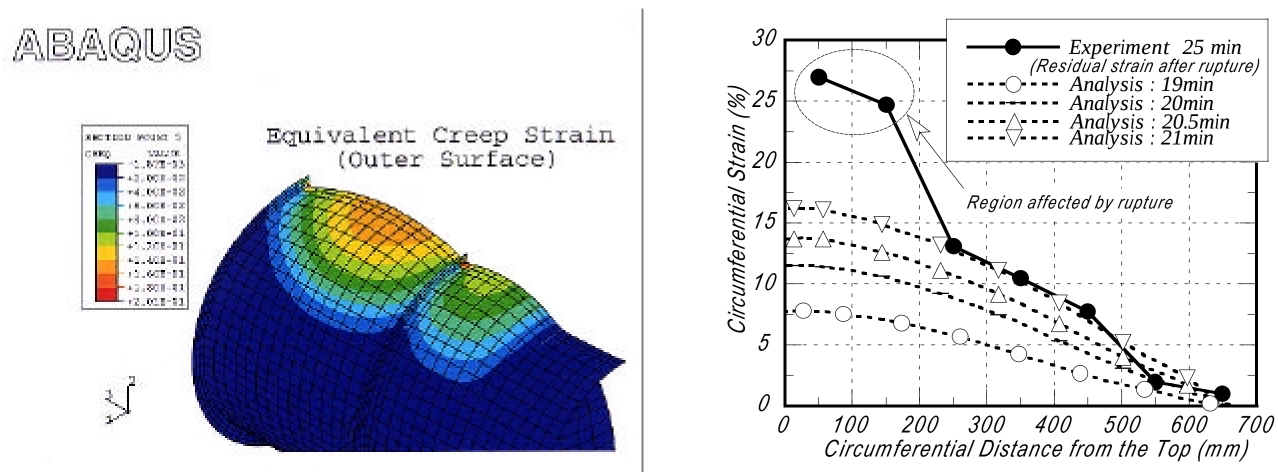



Fig.8 Distribution of Equivalent Creep Strain and Circumferential Strain Distribution Calculated by the ABAQUS Code for the Rupture Test A Performed in PEECHEUR Program

### Mechanical Characteristics of the 48Y-Cylinder for IAEA Fire Test Requirement

The mechanical integrity of the natural $UF_6$ transport container under the IAEA fire test condition was assessed by the proposed analysis method. The thermal loading for IAEA requirement consists of transient temperature distribution and inner pressure applied on the inner surface of the shell, which follows values obtained in calculations of the DIBONA-2D code as shown in Fig.2. The additional heat input from the stiffening ring of the cylinder was not taken into account.

Initial conditions are as follows.

- Initial Temperature : 38 degrees
- Initial Pressure : 0.044MPa for saturated pressure of $UF_6$ solid at 38 degrees
- Atmospheric Pressure : 0.1MPa
- $UF_6$ Dead Load : Modeled by hydraulic pressure on the inner surface
- Cylinder Dead Load : Mass density is set to 7.85g/cm$^3$

Fig.9 shows the deformation around 27 minutes thermal loading. As the considerable temperature difference in the circumferential direction exists near $UF_6$ surface level, highly stressed region (Mises stress exceeds 180Mpa) is occurred and the maximum equivalent creep strain is reached to 40%. It is found that creep damage factor also exceeded 0.25. As a result, due to the considerable creep deformations, rupture possibility of the natural $UF_6$ transport container in the IAEA fire test condition will be possibly high without thermal insulation system.

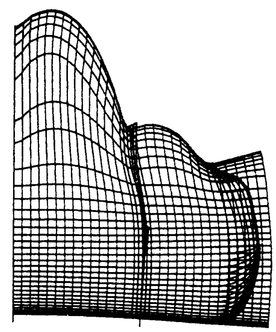


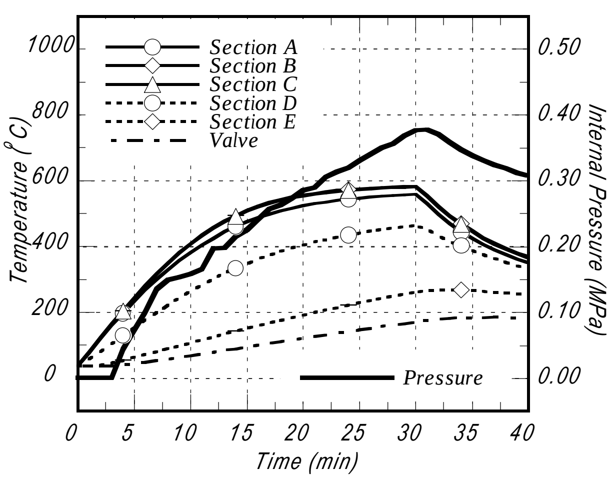
Fig.9 Deformation around 27 Minutes Thermal Loading (Magnification of 10 times)

**SAFETY ANALYSIS OF INSULATED 48Y-CYLINER UNDER IAEA CONDITION**

In Japan, 48Y-cylinders are transported with the heat protect system considering the hypothetical fire conditions as shown in Fig.10. To evaluate the safety of insulated transport container for natural $UF_6$ with the Japanese heat-protective covers, the thermal-mechanical analysis was performed with ABAQUS code considering the fire test condition specified by the IAEA regulation in 1996.

Fig.11 shows the time histories of the steel, valve and internal pressure. Max. temperature of the container and the internal pressure are 584$^{o}$C and 0.4MPa, respectively. Moreover, as maximum temperature of the filling valve is below 200$^{o}$C, the leakage of $UF_6$ can be avoidable. Fig.12 shows the distribution of the equivalent creep strain at the 30 minutes thermal loading. Only 0.02% creep strain is occurred. Finally it can be concluded that the natural $UF_6$ transport container with the Japanese heat cover system has enough safety margin for the IAEA fire test requirement.

Fig.10 Insulated 48Y-cylinder Equipped with the Japanese Heat-Protective Covers



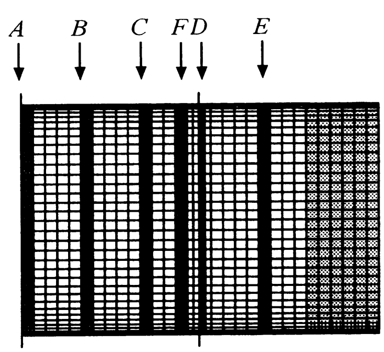




Fig.11 Time Histories of the Steel, Valve and Internal Pressure of the Insulated 48Y-cylinder

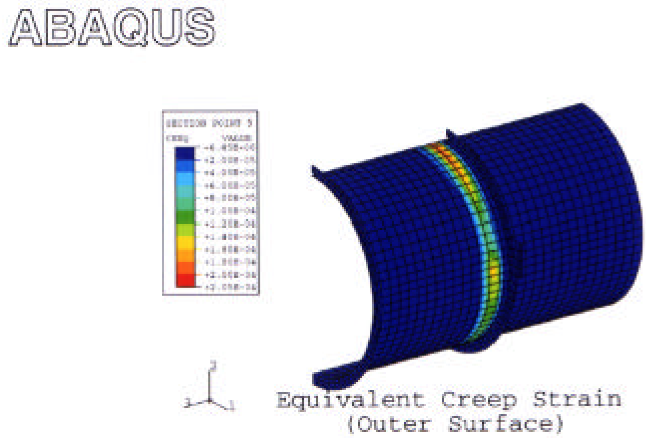



Fig.12 Distribution of the Equivalent Creep Strain at the 30 minutes Thermal Loading for 48y-cylinder with Heat Cover System

**SUMMARY**

IAEA, in accordance with the revision of the regulation in 1996, established regulation for $UF_6$ transportation taking into account chemical hazards. The fire test (800°C for 30 minutes) became a requirement for the natural $UF_6$ transport container. CRIEPI and IPSN had already terminated the first joint research work (TENERIFE Program) to make clear the thermal-physical behavior of $UF_6$ in a transport container under fire condition and confirmed the occurrence of the rapid increase in interior pressure. On the other hand, ASTM SA516 carbon steel for moderate and low temperature service is now used as the structural material for this type of cylinder. As the structural strength of the cylinder material decreases and creep effect does not also become negligible with increasing temperature, it is very important to evaluate the thermal-mechanical behavior of $UF_6$ cylinder under fire condition, especially the possibility of rupture of the cylinder. Therefore, CRIEPI and IPSN performed the rupture test with the large scale container in the second joint research work (PEECHEUR Program) to clarify the mechanical characteristics of the container under high pressure at high temperature. Moreover, according to the various material tests with ASTM SA516 carbon steel at high temperature performed by CRIEPI, the formulation of the material model considering the creep effect and rupture criteria were proposed, and this constitutive model was applied to ABAQUS code. According to the numerical results, the mechanical phenomena of the cylinder under the IAEA fire test requirement was investigated and the safety margin for the rupture of the insulated 48Y-cylinder was verified.

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