71-3077

U.S. Department
of Transportation
**Pipeline and
Hazardous Materials
Safety Administration**

400 Seventh St., S.W.
Washington, D.C. 20590

APR -1 2005

Mr. William Brach, Director
Spent Fuel Project Office
Office of Nuclear Material Safety and Safeguards (NMSS)
U.S. Nuclear Regulatory Commission
Washington, DC 20555

Dear Mr. Brach:

In accordance with the Memorandum of Understanding between our Agencies, I request your review and comment on the enclosed thermal analysis of 48 inch cylinders containing natural uranium hexafluoride.

In order to develop a U.S. position on the ability of these cylinders to meet the thermal test requirements of 10 CFR 71, we plan to meet with the authors of this report in approximately ninety days. We would welcome your participation in this meeting and request that you provide your comments within the next sixty days.

If you have any questions or are unable to meet our proposed schedule, please feel free to contact me at (202) 366-4545.

Sincerely,

Richard W. Boyle, Chief
Radioactive Materials Branch
Office of Hazardous Materials
Technology

Enclosure

NMSS01

November, 2004

Subject: Investigation of 48-inch diameter UF_6 Cylinders in Fire

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Abstract.

An investigation of the 48-inch diameter cylinder behavior in the regulatory fire test was performed to determine the survivability of the 48-inch diameter cylinders in the hypothetical fire. The U. S. Department of Transportation (DOT) regulations incorporate the thermal test requirement of the International Atomic Energy Agency (IAEA)'s regulation, TS-R-1. The regulations stipulate that the cylinders must survive 30 minutes in an 800° C fire. Historically, the 48-inch diameter cylinders transporting natural or depleted uranium have been shipped without any protective overpack. The task is to determine whether any or all of the 48-inch cylinders with full capacity meet the IAEA thermal requirement. This study used a simulated numerical model that was constructed with Tenerife research project's experimental data relevant to the 48-inch diameter cylinders. The Tenerife UF_6 cylinder test data is, by far, the best data available on the behavior of the 48-inch diameter UF_6 cylinder during the IAEA fire test condition. The observation of Tenerife data and the result of this numerical model indicate that,

- There is no cylinder rupture by hydraulic pressure for all 48-inch diameter cylinders in 30 minutes
- There is no cylinder rupture by vapor pressure for thick wall 48-inch diameter cylinders
- Thin wall cylinder may rupture within 30 minutes by hoop stress failure at the top of cylinder where the temperature is the highest.

Investigation of 48-inch Diameter UF_6 Cylinders in the TS-R-1 Regulatory Thermal Environment

Submitted by:
Shin H. Park, Ph.D., Consultant, Oak Ridge, TN, USA;

November 2004

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1. INTRODUCTION

The U. S. Department of Transportation (DOT) regulations incorporate the thermal test requirement of the International Atomic Energy Agency (IAEA)'s regulation, TS-R-1. The regulations stipulate that the cylinders must survive 30 minutes in an 800° C fire. There are a large number of 48-inch diameter cylinders in the industry that historically have been used to transport natural and depleted uranium hexafluoride (UF_6) without additional thermal protective devices.

The purpose of this study is to determine the capability of any or all of the 48-inch diameter cylinders with full capacity meeting the new IAEA thermal requirement. In the absence of any prototype cylinder rupture data in the hypothetical fire, or a reliable numerical model capable of predicting the cylinder rupture time accurately and confidently, an analysis was needed, based on credible experimental data that is closely related to the 48-inch diameter cylinders. The most relevant information, either from the experimental studies or numerical models, is the Tenerife test data. Since the Tenerife test was conducted with a one-third length 48Y UF_6 cylinder in full capacity (62% of solid volume in the test cylinder), a simulated numerical model constructed based on the Tenerife data would be credible. This model was used to predict the temperatures and pressure of the 48-inch diameter cylinders with a full capacity. This numerical model was constructed using the Tenerife test number 4 data (Ten4), which is the most relevant data to this study among the six tests conducted. (Appendix A and Table 3 explain why the Ten4 data are more relevant than the other five tests.) The model constructed based on the 19.5-minute of heating in Ten4 is extrapolated to 25-35 minutes to calculate the temperatures and pressure of 48-inch diameter cylinders. This is the most credible data available closest to the 48-inch diameter cylinders; the data demonstrates the cylinder behavior during the cylinder's exposure to an 800° C fire. The results of the study indicate that a thick wall cylinder will meet the thermal requirement of surviving 30-minutes in an 800° C fire. However, a thin wall cylinder may rupture by the hoop stress failure on the top of the cylinder (above the vapor space) by a combined increase in the cylinder wall temperature and pressure.

2. REVIEW OF RELATED STUDIES

There is considerable information on the thermal behavior of liquid-filled cylinders and a few studies of solid-filled cylinder behavior. Most of the experimental studies were conducted in small containers and at temperatures lower than 800° C. There are a few experimental studies conducted with liquid UF_6 and a few with solid UF_6. Most of these experimental studies were conducted either to validate numerical models or to provide measured values for an improved understanding of the heat transfer relationship. There are a few two-dimensional finite element models that calculate the cylinder temperatures and pressure. However, historically there has been no numerical model that could predict accurately and confidently the survivability of any 48-inch diameter cylinder for 30 minutes in an 800° C thermal environment. The French Atomic Energy Commission (CEA)[1] has developed a 2-dimensional finite element model called DIBONA in association with the Tenerife program and it may be the model that could closely predict the cylinder rupture time. The model has been continuously modified and improved with the inputs from the Tenerife tests. The model was validated with Ten4 data and calculated a pressure of 28 bars at 1,800 seconds. These results were compared to a measured value of 20 bars (the heating was stopped at 19.5 minutes and the pressure rise beyond this point was due to the energy emanated from the cylinder wall).

The British Nuclear Fuels plc (BNFL)[2] has conducted a numerical study of 48-inch diameter cylinder in association with the structural analysis of the cylinder wall. BNFL calculated the highest cylinder wall temperature of 660° C at a narrow area on top of the cylinder, with cylinder temperature decreasing toward the bottom of the cylinder. Based on this temperature profile and the cylinder with A-516 steel, BNFL estimated that the cylinder would rupture at an internal pressure of 42 bars. BNFL also estimated that there would be a 17% plastic deformation before breaking of the cylinder wall. The study did not include the influence of the stiffening rings, but if it were added, the cylinder's capability to survive in a fire would be enhanced.

The Central Research Institute of Electric Power Industry (CRIEPI)[3] of Japan has conducted an experiment to measure the emissivity of A-516 steel. The emissivity measured was 0.4 for the temperatures below 400° C and 0.6 for above 400° C. This is lower than the 0.8 emissivity assumption used in the IAEA Coordinated Research Program. The Tenerife calibration test also showed a measured heat flux in an 800° C oven temperature that was lower than the IAEA specified heat flux, indicating that the emissivity of the cylinder external surface may be in the 0.5 - 0.6 range. Nevertheless, for conservatism, 0.9 and 0.8 emissivities for fire and cylinder respectively were used in this analysis.

CRIEPI[4] also conducted a numerical study of 48Y cylinder with a finite element method and concluded that,

- There would be no cylinder rupture by hydraulic pressure within 30 minutes
- There would be no cylinder rupture by gas pressure within 30 minutes

R. Lewis[5] of the University of Wales constructed a 2-dimensional finite element model of the UF_6 container under the IAEA fire test condition. Where data on heat transfer coefficients were not available, the model used assumed values to include their effect. The study was focused on the mechanisms of UF_6 thermal behavior and was not validated. However, the study concluded that it would be unlikely for the cylinder to rupture from hydraulic pressure but there was a possibility that the cylinder could rupture by vapor pressure.

The numerical models described above were constructed to describe the behavior of UF_6-filled cylinders in a fire. However, there has been a lack of consensus among international analysts on the reliability of the models' predictions of cylinder rupture time. There are numerous reasons for the questions on the reliability of the models. One is the paucity of credible data to validate the models. Others are associated with the complexities and unknowns associated with the UF_6 evolution during a cylinder's exposure to a fire. Some of the unknowns are:

- Absence of information on UF_6 mass transfer rate across the liquid surface
- Difficulty of modeling the solid UF_6 sinking and its effect on temperature profile
- Difficulty of predicting the onset of boiling and determining the boiling heat flux

The task becomes more difficult with the variation in the cylinder wall temperature and the formation of a stable stratified liquid layer. It is also known that a large number of variables are involved in boiling heat transfer process and neither general equations describing the boiling process nor general correlation of boiling heat transfer data are available to date, especially with UF_6. There is also concern on how to treat the cylinder valve in the study. It has been known that the valve tinning made of a tin and lead mixture melts around 200° C, resulting in releasing UF_6. This release would delay the pressure rise in the cylinder, depending on the leak rate. However, for conservatism and consistency with the IAEA Coordinated Research Program, the effect of a leak through the valve was not included in this study.

3. BACKGROUND OF CYLINDER RUPTURE STUDY

A cylinder will rupture when the hoop stress developed by the cylinder pressure exceeds the ultimate tensile stress of the cylinder wall. Cylinder pressure may be the vapor pressure of UF_6 or the hydraulic pressure of UF_6 expansion when a cylinder is filled completely with UF_6 in solid, liquid or a combination of the two.

A cylinder rupture test was conducted at the Oak Ridge Gaseous Diffusion Plant (ORGDP)[6] where cylinders of various sizes were pressurized to rupture at room temperature. Table 1 shows a portion of the test result. The table also presents data on hoop stress and ultimate tensile strength (UTS) of the cylinders. The hoop stress was calculated based on the rupture pressure of the cylinders. The UTS was based on the BNFL study mentioned above. The BNFL research was conducted on a cylinder that had been designed with a minimum UTS of 55,000 psi. The UTS vs. temperature data used in this report is consistent with the BNFL study[2].

Table 1. ORGDP Cylinder Rupture Test at Room Temperature (Data obtained and/or derived from ORGDP Study[6])

Cylinder	Material	Thickness Inch	Rupture Pressure psi	Hoop stresses psi[1]	UTS psi[2]
8A	Monel	3/16	2,950	62,900	64,000
48OM	A-285	5/16	870	66,820	70,000
48Y	A-516	5/8	1,770	67,970	70,000
48A	A-285	5/8	1,285	49,340	70,000

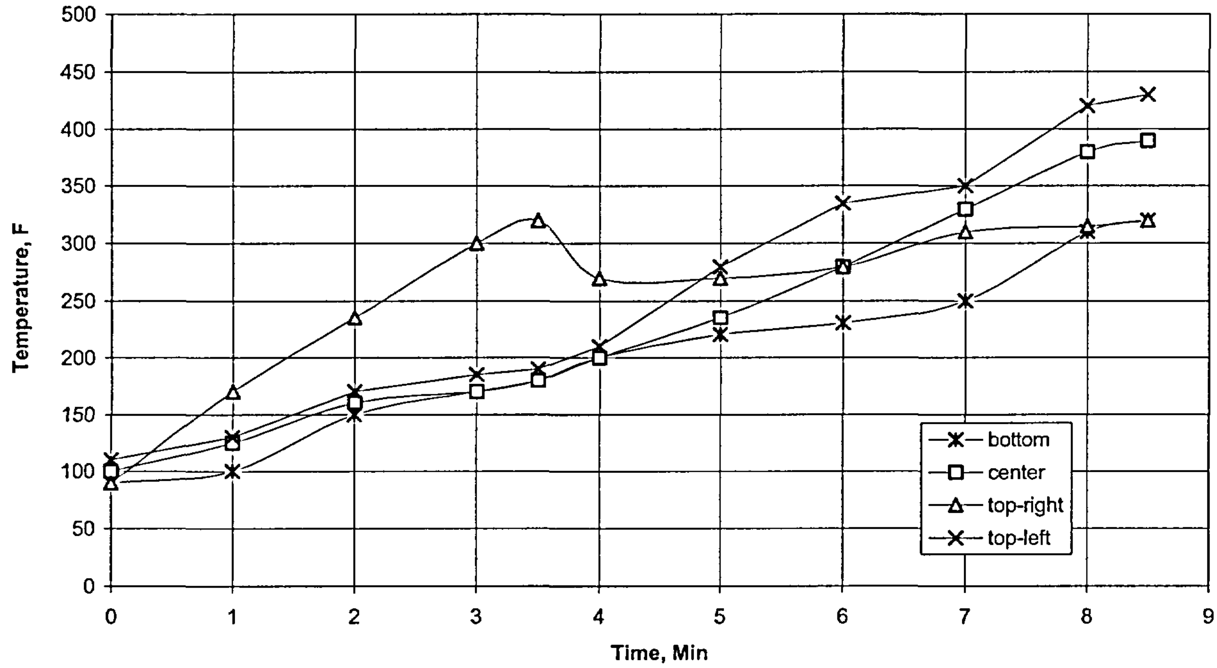
Notes:

1. Hoop stress was calculated based on rupture pressure of cylinder and falls within the range of ASTM standards
2. UTS values are based on BNFL study and ASTM standards

The hoop stresses calculated from the cylinder pressures at rupture is fairly close to the ultimate tensile stresses (UTS) of the cylinder material at room temperature, confirming the hydraulic rupture mechanisms. The rupture pressure of 48OM cylinder with a thin wall cylinder is about a half that of the 48Y cylinder, indicating the direct correlation of the cylinder wall thickness to the rupture mechanism.

A.J. Mallett[7] conducted a series of cylinder rupture tests with UF_6 at the Oak Ridge Gaseous Diffusion Plant. This may be the only UF_6-filled cylinder fire test in an open atmosphere environment. Figure 1 shows the temperatures measured during a test with an 8A, *i.e.,* 8-inch diameter, cylinder with 245 lb. of depleted UF_6. The cylinder exploded at around 8.5 minutes in the 650°-700° C fire. The UF_6 temperature measured at rupture was around 320° F (160° C) and the cylinder wall was about 1,100 F° (600° C). At this condition, the cylinder would have been filled completely with liquid UF_6 and would be ruptured by the hydraulic pressure of the liquid UF_6 expansion.

Figure 1 – 8A Cylinder Fire Test at ORGDP, 1966



A crude energy balance calculation shows that the energy required to reach the measured temperatures was about 81,500 Btu while the average rate of energy absorbed by the cylinder during the cylinder's exposure to the fire was about 125,000 Btu/hr. This shows that the hydraulic rupture would have occurred in about 10 minutes, which confirms the hydraulic rupture scenario within a margin of error in the estimation of the radiant energy absorbed by the cylinder, which was calculated with average fire and cylinder wall temperatures

The Tenerife test data is the most relevant to the investigation of the 48-inch diameter cylinders. However, there are two areas of concern in using the Tenerife data to the analysis of the 48-inch diameter cylinders. These are,

(1) None of the Tenerife cylinders was heated to rupture during the tests
(2) The Tenerife test cylinders are 1/3 the length of 48Y cylinders.

Since all the Tenerife tests were stopped short of rupturing the cylinders, the data is credible until the heating stopped. The ratio of the UF_6 mass in a cylinder to the heat transfer surface area has a direct effect on a system where the radiation is the dominant heat transfer process. This also has a direct impact on the interpretation of the Tenerife data to apply to other cylinders. Table 2 shows a comparison of the Tenerife cylinder with 48-inch and 8-inch diameter cylinders with a full capacity where there are noticeable differences in the ratio of the mass to heat transfer surface area. Hence, the 19.5-minute of heating in Ten4 would have the same effect of 24-minute of heating to 48Y and 23-minute of heating to 48X cylinder.

Table 2. Comparison of the Mass to Heat Transfer Areas of Cylinders

Cylinder	Tenerife	8A	48X	48Y	48G
Mass, lb	9,760	245	21,030	27,560	28,000
Heat transfer area, sq. ft.	71.95	8.61	133.6	167.8	164.1
Mass/Area	135.6	28.46	157.4	164.2	170.6
Ratio to Tenerife cylinder[1]	1	.21	1.16	1.21	1.26
Equivalent of 19.5 minute[2]	19.5	--	22.6	23.6	24.6

Notes:

1. The multipliers of 1.16 and 1.21 for the 48X and 48Y cylinders, respectively, are calculated by dividing the Mass/Area values for the 48X and 48Y cylinders by the Mass/Area value for the Tenerife cylinder. This multiplier was established by applying heat transfer logic to interpolate Tenerife data for standard cylinder types.
2. The equivalent minutes for the 48X, 48Y and 48G cylinders were calculated by multiplying the Tenerife minutes by the multipliers.

The Tenerife tests, even though the tests did not last long enough to rupture the cylinders, provide valuable information on the UF_6 evolution during the cylinders' exposure to a fire. Some of the important information is:

- There are two different patterns of the UF_6 evolution in a cylinder, due to the geometrical differences, *i.e.*, the upper half and lower half sections.
- The upper section consists of the UF_6 surface facing the cylinder inner wall through the vapor space
- The heat transfer processes in the upper section are radiation, convection in vapor space, and evaporation and condensation of UF_6 across the UF_6 surface
- The lower section consists of the bulk UF_6 surrounded by the cylinder wall
- The heat transfer processes in the lower section are conduction, boiling along the cylinder wall, and convection in liquid UF_6 regime
- The liquid surface in the upper section becomes stably stratified due to the temperature gradient effect and bulk liquid agitation from the lower section is not sufficient to overcome the stratification
- There is a large temperature gradient around the cylinder wall, the highest at the top and the lowest at the bottom of the cylinder
- The cylinder pressure measured from the vapor space agrees well with the saturation pressure of liquid at the UF_6 surface
- With the variations of the temperatures in the cylinder wall and UF_6, the pressure measurement seems to be the most reliable data.

- Tenerife test number 4 is the most useful data with the IAEA accident scenario in the closest to a prototype cylinder in size.

At the end of the 19.5-minute of heating in the Ten4 test, which is equivalent of 24-minute of heating to 48Y cylinder, the following parameters were measured:

Wall temperature at the top of cylinder ----------------------	528° C
Wall Temperature at the bottom of cylinder -------------------	122° C
UF_6 temperature at surface --------------------------------	~ 110° C
Average liquid UF_6 temperature in lower section -----------	~ 75° C
Pressure measured in void space -----------------------------	6.5 bars

It is estimated that about 57% of the UF_6 mass is in liquid phase with an average temperature of about 100° C at the end of the Ten4 heating. At this condition, the volume occupied by the UF_6 solid and liquid is about 80% of the test cylinder volume.

4. CYLINDER RUPTURE STUDY AND RESULT

A. Determination of hydraulic cylinder rupture

The condition for hydraulic rupture of a 48Y cylinder is investigated for this report, along with the construction of a cylinder model. The hydraulic rupture condition is determined with an energy balance between the energy absorbed by a cylinder and the energy level causing the hydraulic rupture of cylinder. The energy level causing hydraulic rupture is the sum of the energy absorbed by the cylinder wall and UF_6. When the average liquid UF_6 temperatures measured during the Tenerife tests are around 100° C, the energy level to cause hydraulic rupture is about 2.25e06 Btu. However, a crude estimation of the sum of the radiant energy absorbed by the cylinder in 30 minute is lower than the hydraulic rupture energy level. This indicates that a 48Y cylinder would not be ruptured by hydraulic pressure in 30 minutes in an 800° C fire. However, there is a possibility of cylinder rupture by the vapor pressure with the degradation of the tensile stress of the cylinder wall at elevated temperatures. This model calculates the total radiant energy absorbed by the cylinder and compares that with the energy level causing the hydraulic rupture. This model also calculates the hoop stress at the top of the cylinder where the temperature is the highest, to determine the possibility of cylinder rupture by the vapor pressure.

B. Model Description

A simple numerical model was constructed based on the Ten4 data of 19.5-minutes of heating. This model calculates the temperatures and pressure separately for the upper and lower sections. It is reasonable, from the analysis of the Tenerife data, to study the cylinder in two sections since there is a minimum effect of liquid UF_6 mixing between the two sections. This absence of mixing is due to the stable stratification of the liquid layer. The heat transfer processes of the conduction, convection, radiation, and boiling are used in each regime, as described above. However, the model requires a few corrections in the heat transfer parameters to include the complex behavior of UF_6 during a cylinder's exposure to a fire. These corrections are made based on the analysis of the Ten4 test data. Some major reasons for such corrections are:

- Inability to correctly quantify the evaporation and condensation rate of UF_6 across the liquid surface,
- Difficulty of modeling the downward movement of the UF_6 solid and its effect on the temperature profile
- Inability to predict the inception of boiling along the cylinder wall in the lower section and determining the boiling heat flux
- Inability to quantify the solid UF_6 melting rate.

Some of the reasons for the inability to correctly estimate the above are:

- the temperatures and pressure in a cylinder are in transient and varying continuously
- the liquid UF_6 temperature at the surface is not uniform across the surface, and in fact, is higher at the middle and lower at the ends contacting the cylinder wall
- the boiling depends on local liquid UF_6 temperature and pressure along the cylinder wall
- the task of determining the onset of boiling becomes more difficult with varying cylinder wall temperatures from the top to bottom

The above processes were not factored into this numerical model. Doing so would have required making assumptions that would need to be validated with actual data that is currently unavailable.

However, this model agrees fairly well with the Ten4 data to the end of the Tenerife test heating. This validates the model's algorithms and the heat transfer parameters in the model. The model calculates the hoop stress developed from the cylinder pressure and compares that with the ultimate tensile stress of the cylinder wall at elevated temperatures. The model calculates the sum of the radiant energy absorbed by the cylinder and compares that with the energy level that would cause the hydraulic rupture.

C. Results

This model is validated with the Ten4 data. Figure 2 shows the temperatures and pressure of a thick wall cylinder in the upper section. The modeling results show good agreement with the Ten4 data. The radiant heat transfer rate from the fire to the cylinder was calculated with emissivities of 0.9 and 0.8 for the fire and cylinder surface, respectively. As mentioned above, the 0.9 and 0.8 emissivities are used for conservatism and in keeping with those used for the IAEA Coordinated Research Program. The heat transfer process from the cylinder wall to UF_6 is a combination of radiation, convection in vapor phase, and evaporation and condensation of UF_6 across the UF_6 surface. A convective heat transfer coefficient of 0.1 Btu/min.ft^2 F is used as an effective coefficient that best fits the data and includes the effect of the evaporation and condensation of UF_6.

Figure 2. Comparison of Model's Predicted Thick Wall Cylinder Temperature in Upper Section with Ten4 Data

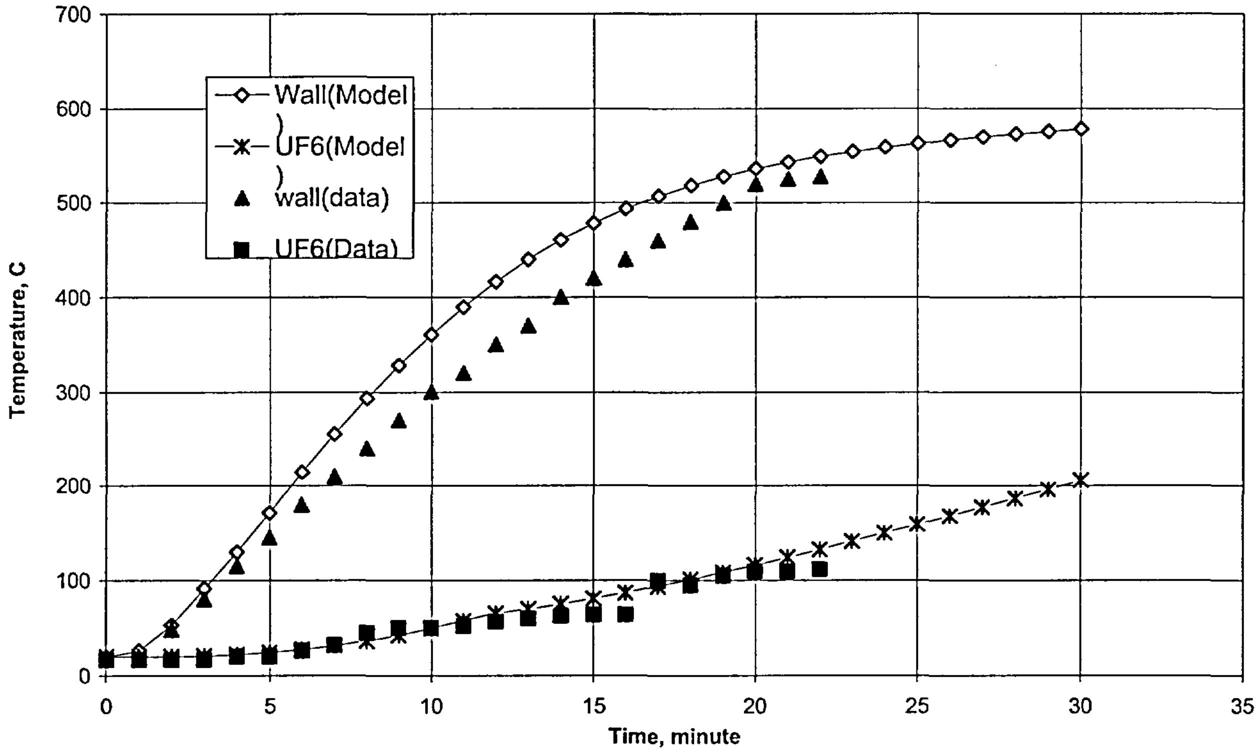


Figure 3 shows a comparison of the pressures between the model results and the Ten4 data. The cylinder pressure calculated is 31 bars in 30 minute, which compares well with the 28 bars obtained by the DIBONA code.

Figure 3 – Comparison of Model's Predicted Thick Wall Cylinder Pressure with Ten4 Data

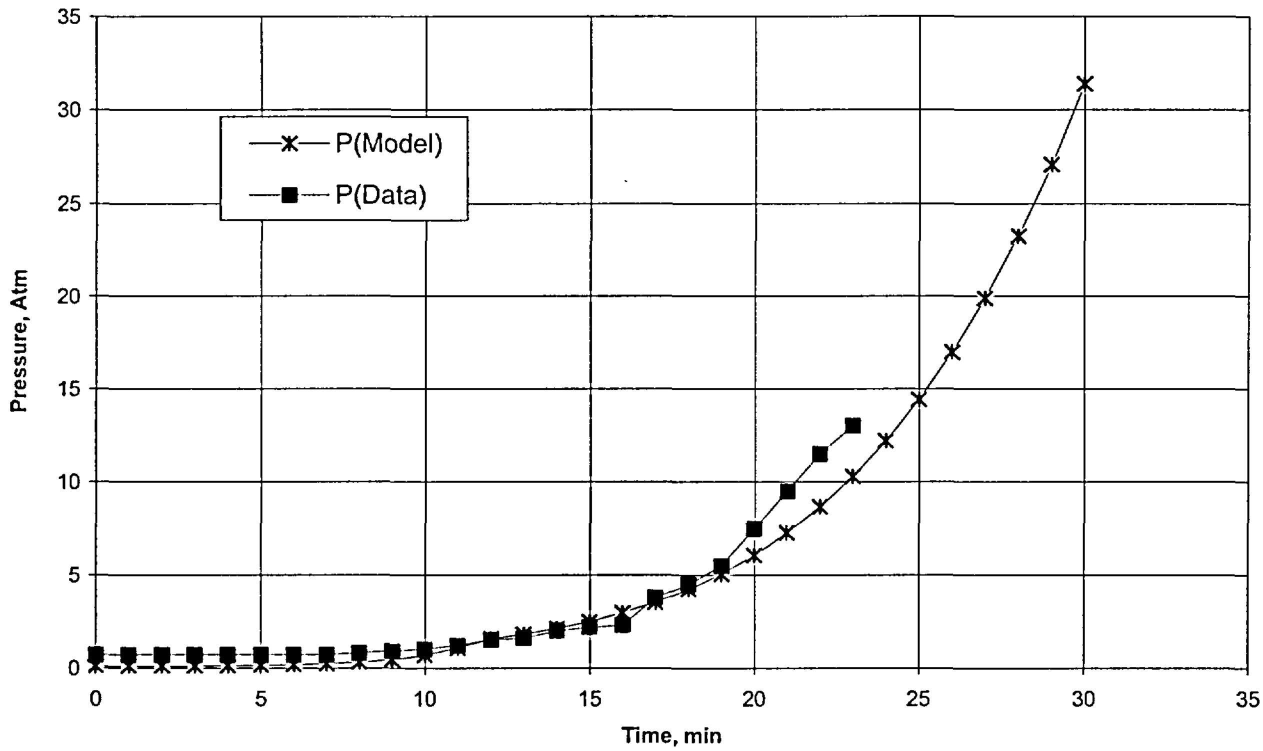


Figure 4 shows a comparison of the model's output and the Ten4 data on temperatures of the cylinder wall and the UF_6 at the lower section of the cylinder. The heat transfer process is far more complex in the lower section, with a natural convection coupled with boiling of UF_6 along the cylinder wall. The onset of boiling depends on the excess temperature and the local UF_6 liquid pressure, and is not possible to model this process accurately. The cylinder wall temperature in the lower section increases rapidly when a cylinder is exposed to a fire, followed by sudden decreases in the wall temperatures. These decreases in temperatures are due to the convection and local boiling. Since the boiling condition and heat flux rate depend on various variables and there is no UF_6 boiling correlation data available, an analytical modeling of the onset of the boiling and determining the boiling heat flux are not possible. This becomes more difficult with a large temperature variation along the cylinder wall, coupled with the solid UF_6 mass shifting. The model assumes the onset of the boiling and boiling heat flux rate from the interpretation of the Ten4 data.

Figure 4 – Comparison of Model's Predicted Thick Wall Cylinder Temperature in Lower Section with Ten4 Data

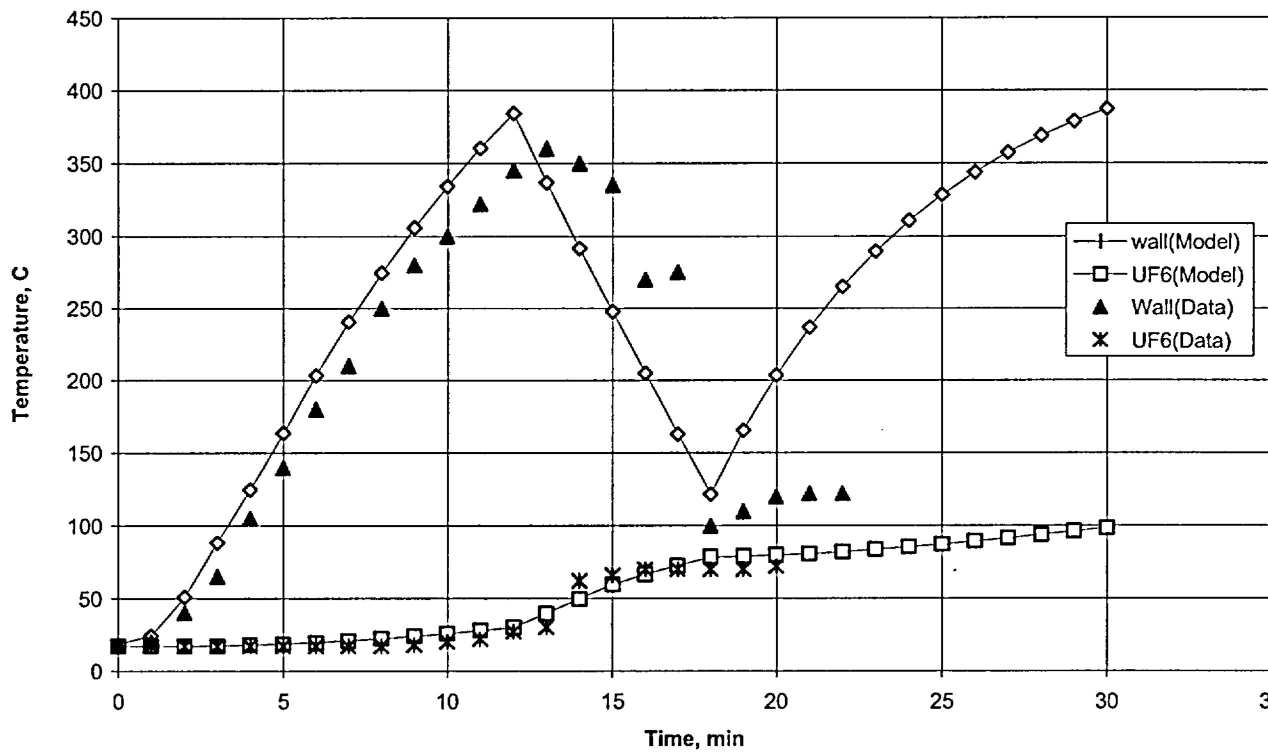


Figure 5 – Comparison of Hoop Stress and Ultimate Tensile Stress (UTS) of 48YCylinder

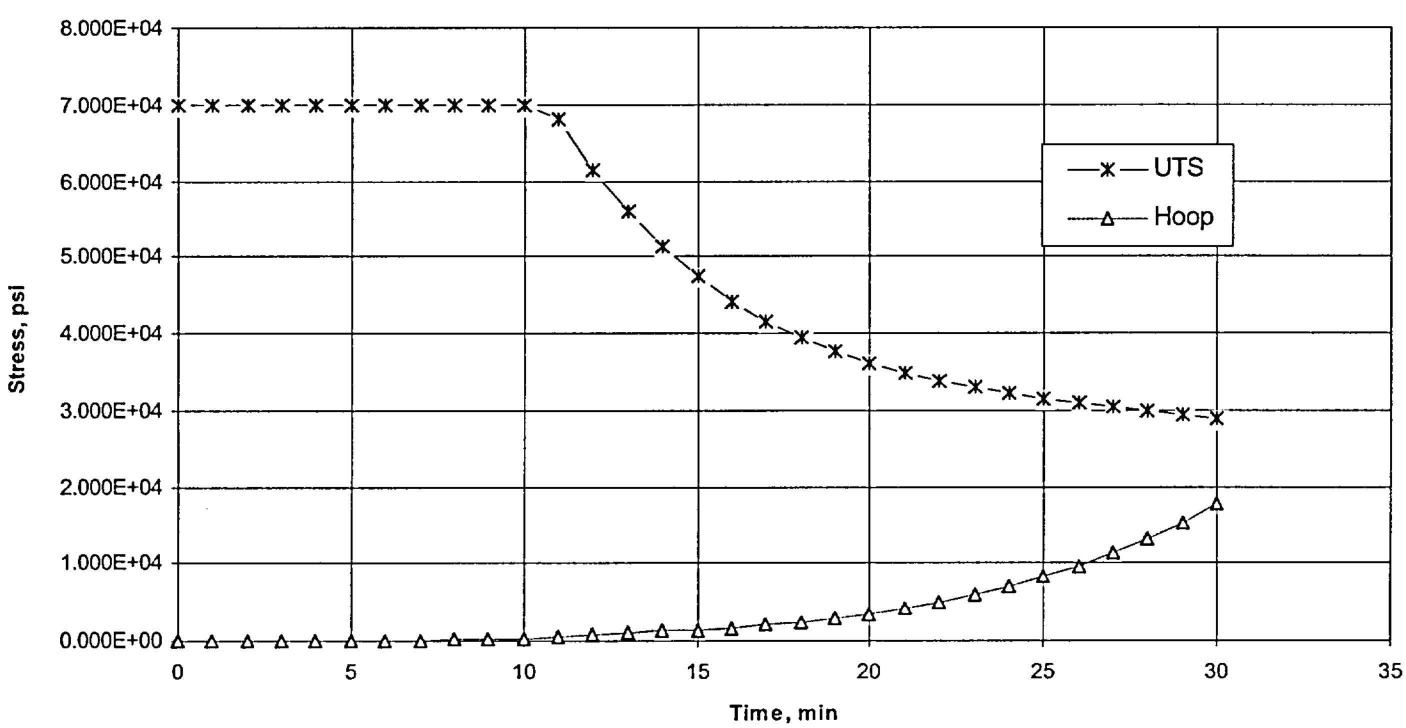
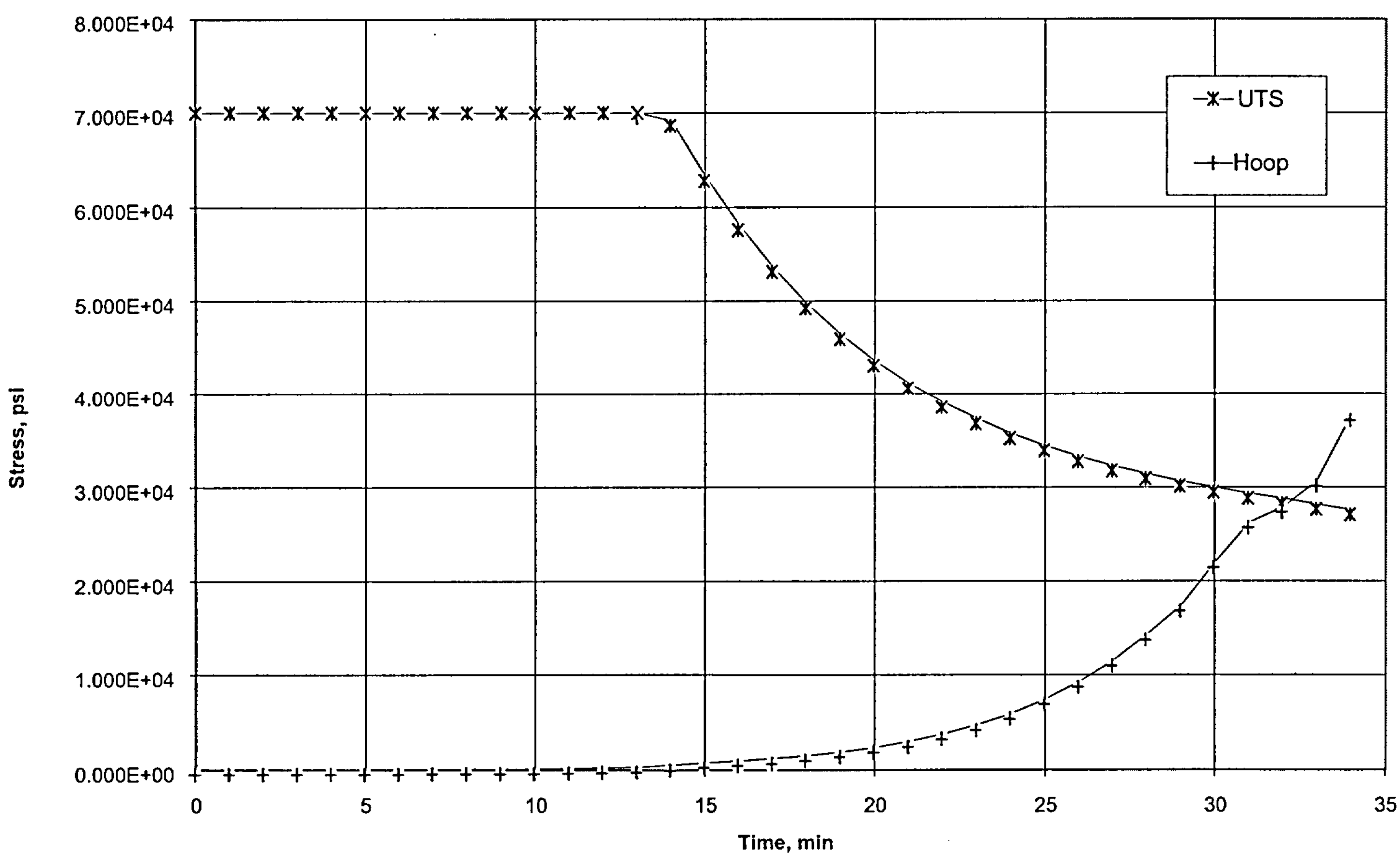


Figure 5 shows a comparison of the hoop stress developed from the cylinder pressure and the ultimate tensile stress of A-516 steel degraded with temperature, as measured in the BNFL study referenced above[2]. The result indicates that the hoop stress of a thick wall cylinder is not strong enough to overcome the ultimate tensile stress of the cylinder wall at the temperatures calculated, even during the 30-minute, 800° degree fire test conditions.

Figure 6 shows an analysis done on the estimated time to rupture the 48Y cylinder. The analysis was done by running the code until the hoop stress exceeds the ultimate tensile stress. The graph shows that rupture of the Tenerife thick wall test cylinder would occur at around 34 minutes in the 800° C fire. The time scale factor between the Tenerife and standard 48Y cylinders is about 1.21, i.e., the ratio of UF_6 mass to heat transfer surface area between 48Y cylinders and the Tenerife cylinder. (See Table 2 for a description of how the multiplier was derived.) Therefore, the 48Y cylinder would rupture around 42 minutes (34 x 1.21).

Figure 6 – UTS vs Hoop Stress Tenerife Test Cylinder with Thick Wall



The observations made from the figures above and the Ten4 data are:

a) There is insufficient amount of solid UF_6 melted to fill the void space of the cylinder in 30 minute to cause a hydraulic rupture
b) There is a potential of a cylinder rupture at the upper cylinder surface by a combination of the high cylinder wall temperature and pressure. However, Figure 5, shown above with a thick wall cylinder, indicates that the hoop stress by the internal pressure at 24 minutes (equivalent to 30 minute to 48Y cylinder) or even at 30 minute is still lower than the ultimate tensile stress of the cylinder wall.
c) The cylinder wall and UF_6 temperatures at the lower section are considerably lower than that of the upper section and would not cause the cylinder to rupture.

Figures 7 and 8 show the temperatures of a thin-wall cylinder in the upper and lower sections, respectively. The wall temperature in the upper section increases rapidly to 600° C with less thermal capacity in the wall, compared to a thick-wall cylinder.

Figure 7 – Temperature Profile of Thin Wall Cylinder in Upper Section

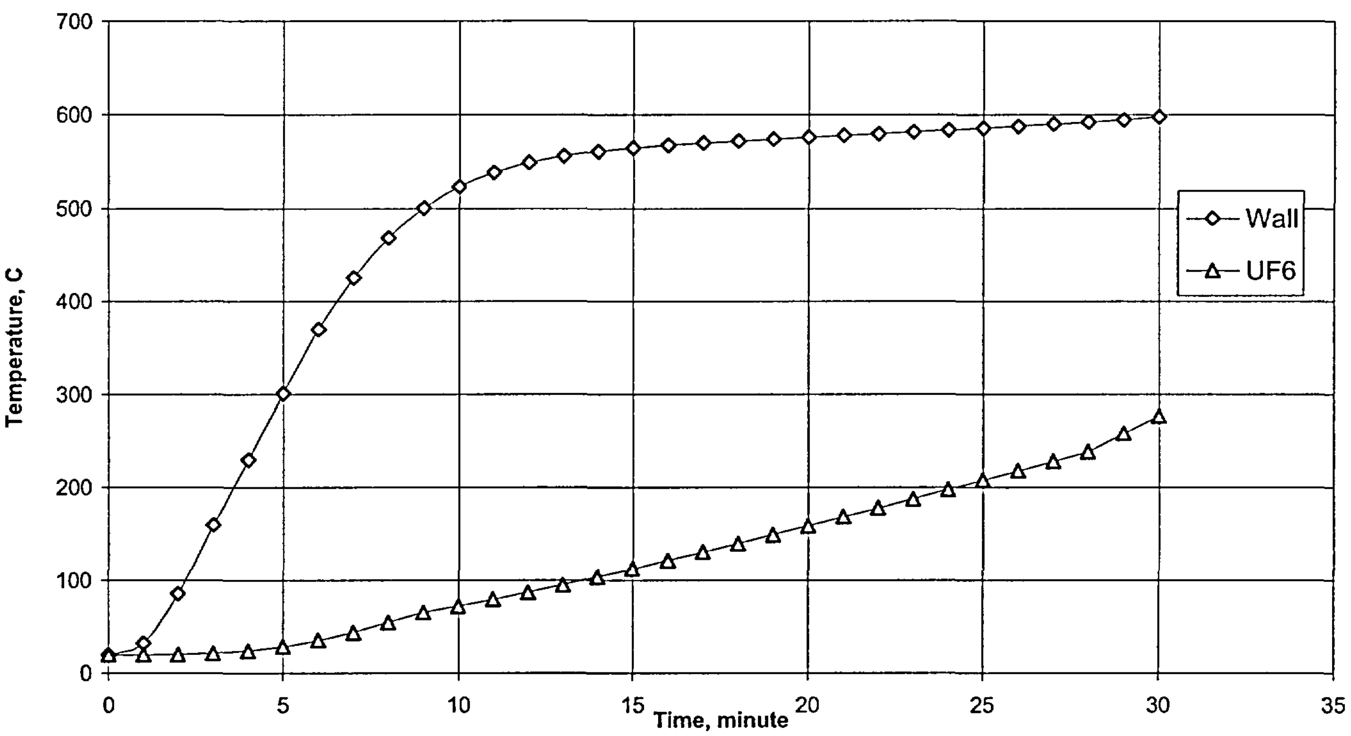


Figure 8 – Temperature Profile of Thin Wall Cylinder in Lower Section

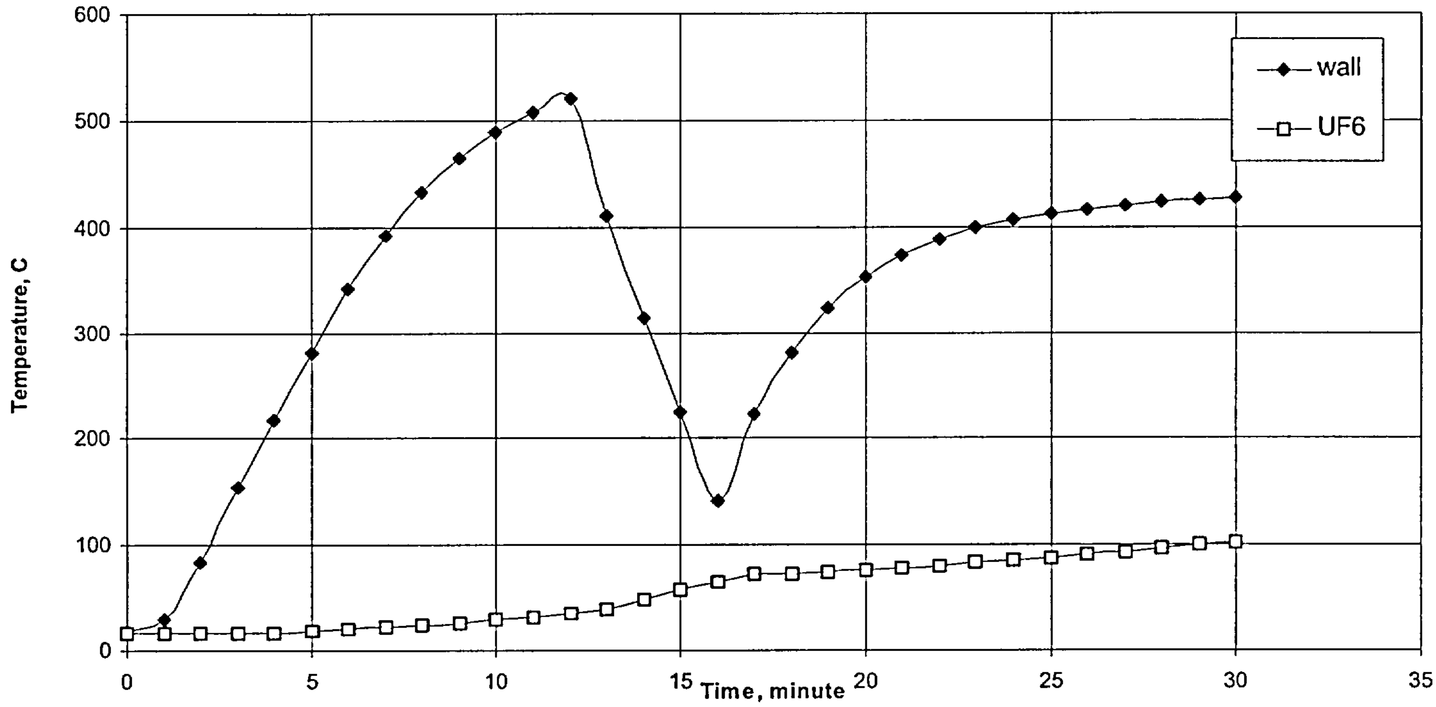
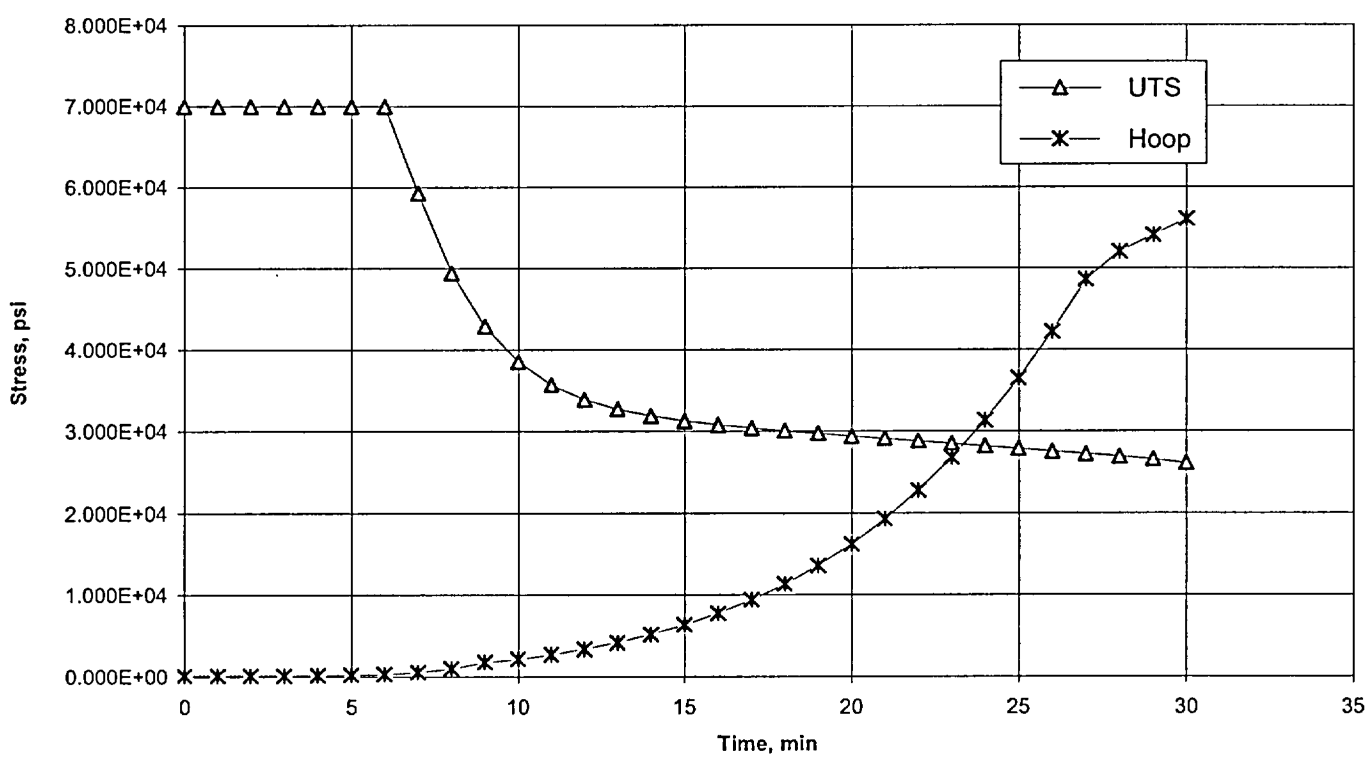


Figure 9 – Comparison of Hoop and Ultimate Tensile Stress of Thin Wall Cylinder



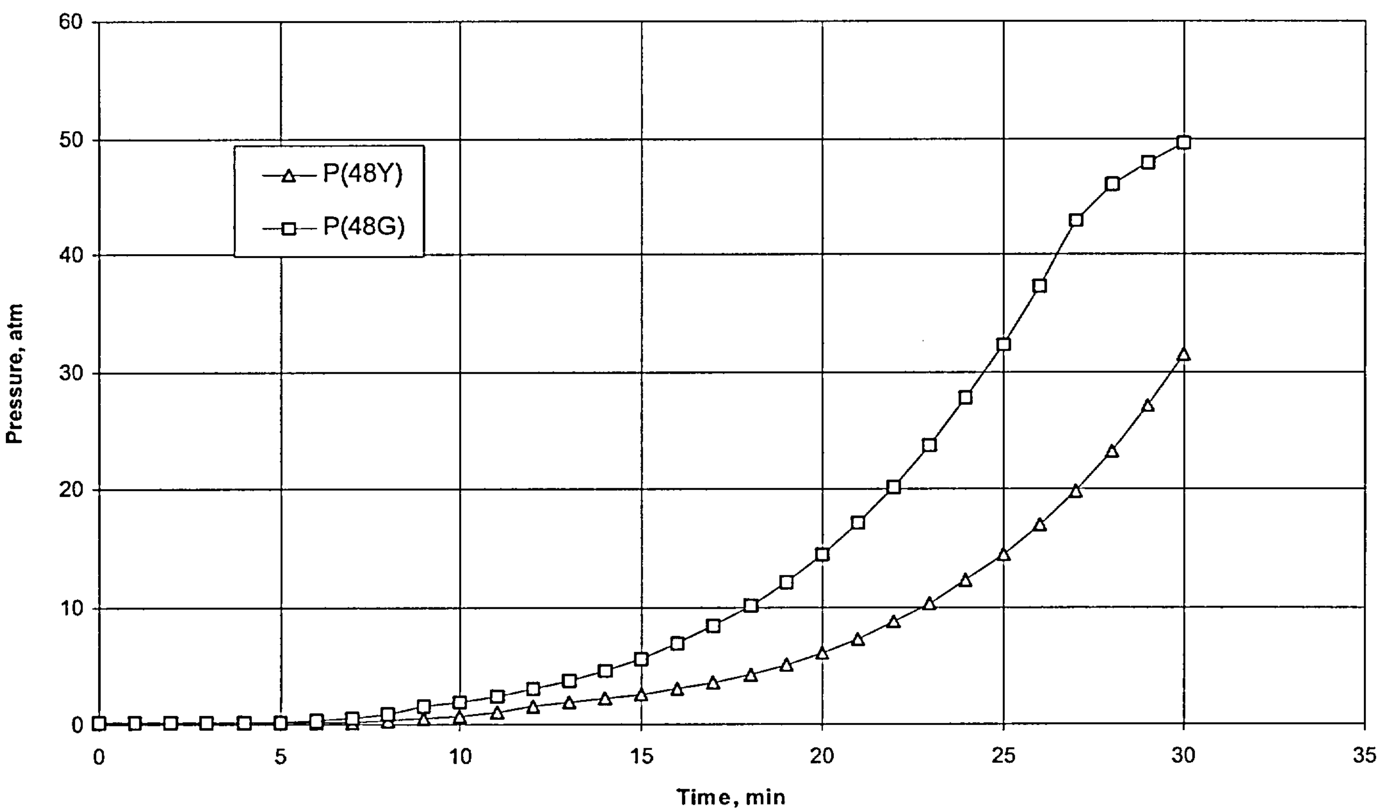
The temperature profile in the lower section, shown in Figure 8, demonstrates a similar pattern of sharp decreases in the cylinder wall temperature with the onset of the boiling. Figure 9 shows the hoop stress developed and compares that with the ultimate tensile stress. The numerical result shows that a thin wall cylinder would rupture in 24 minutes by the vapor pressure of UF_6.

The effects of thinner cylinder wall, comparing the 48G cylinder with the 48Y cylinder, are:

1. Thin wall cylinder temperature increases faster than that of a thick wall due to less thermal capacity.
2. Less energy absorbed by the cylinder wall results in more energy to UF_6 and, consequently, faster increases in the cylinder pressure.
3. Hoop stress increases faster due to a combination of the higher cylinder wall temperature and thinner wall thickness.

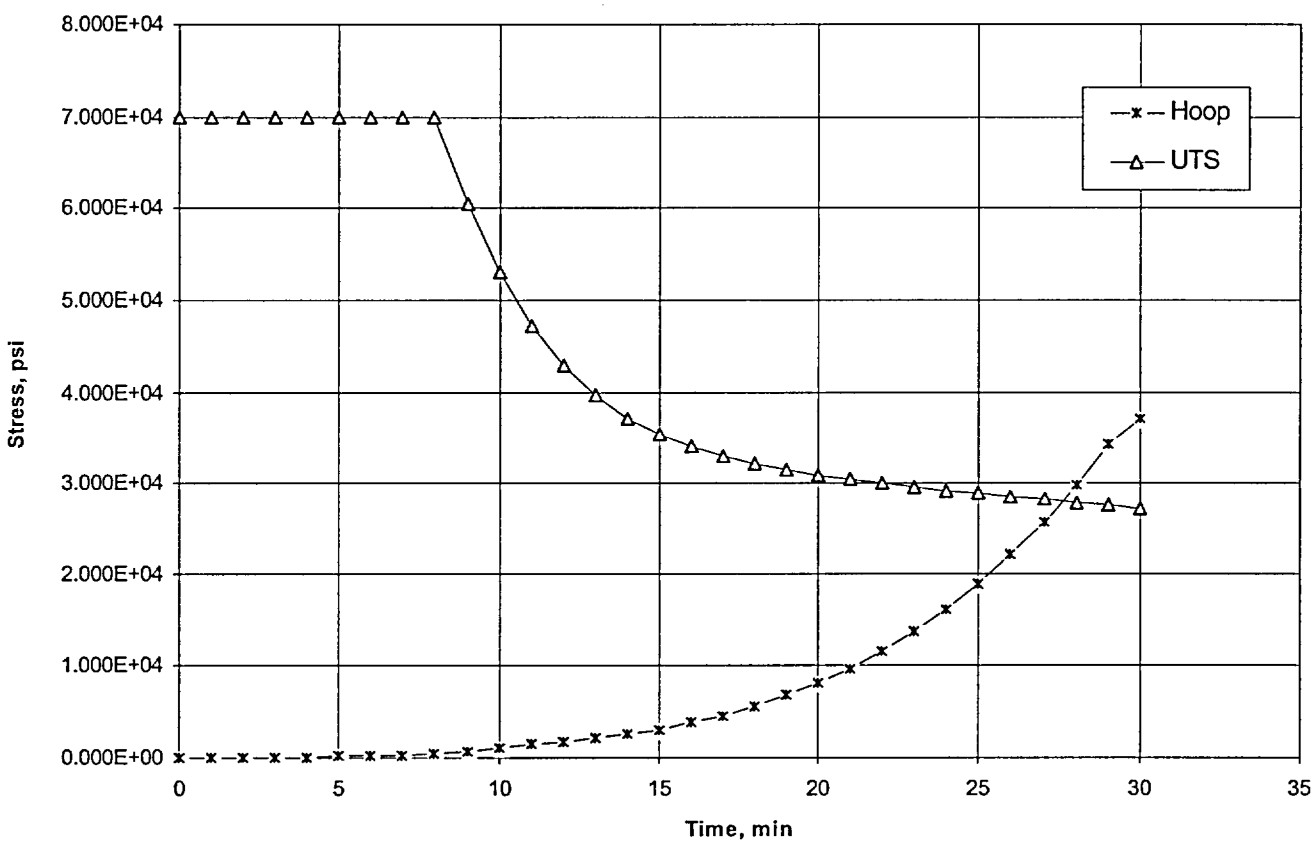
The pressures of 48Y and 48G cylinders are plotted in Figure 10 where the pressure of 48G cylinder increases faster and higher than that of 48Y, showing the effect of the cylinder wall thickness on cylinder pressure.

Figure 10 – Comparison of Pressure in Thick and Thin Wall Cylinders in 800° C Fire



The model simulates a thin-wall cylinder with an addition of a 1/8-inch thick steel shield to increase the cylinder's thermal capacity. Figure 11 shows the hoop stress and ultimate tensile stress of the simulation. The simulation shows that a 1/8-inch thick shield would improve the survivability of a 48G cylinder to meet the new thermal requirement. There may be other measures that can be applied to the cylinder to improve the survivability of a 48G cylinder in a fire, similar to the blanket-type thermal protection (BTP) and composite-type thermal protection (CTP) recently developed for the 48X and 48Y cylinders (see certificates USA/0679/H(U)-96 and USA/0680H(U)-96, respectively). The search for corrective methods for thin wall cylinders should be conducted with the consideration of other factors such as increase to worker dose associated with handling the devices, impacts to conventional worker safety and other operational issues.[8]

Figure 11 – Comparison of Hoop Stress and Ultimate Tensile Stress of a Thin Wall Cylinder with a 1/8-thick steel Shield



5. CONCLUSION AND RECOMMENDATION

The study is conducted by comparing modeling results with the Tenerife data. Despite its limitations with the use of a prototype that was only 1/3 the length of a 48Y cylinder and the fact that the cylinder was not tested to failure, the Tenerife data is by far the most credible data available. The model developed in this study is validated to the Ten4 data and, therefore, is capable of providing reliable estimates of the temperatures and pressure of a filled to capacity 48-inch diameter cylinder. The results show that a 48Y cylinder with a full capacity can meet the thermal requirement of surviving 30 minutes in an 800° C fire. However, the top of a thin-wall cylinder with either A-516 steel or A-285 steel would rupture within 30 minutes, due to the UF_6 vapor pressure. There may be various devices that could be added to the thin-wall cylinders to increase their survivability. These devices should be evaluated in detail, considering the effectiveness of the devices, the increased dose to workers associated with extra handling of the devices, their impact on conventional worker safety and other operational issues. The conclusion of this study is credible since the study was conducted based on experimental data on a near prototype cylinder size, in a thermal condition envisioned by TS-R-1.

6. REFERENCES

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APPENDIX A

1. Description of UF_6 cylinder behavior in a fire

When a solid-filled UF_6 cylinder is exposed to a fire, the cylinder wall temperature increases rapidly due to the low thermal capacity of UF_6 vapor and the thermal conductivity of the solid UF_6. The upper half section (a little less than a half for 62% filled cylinder) of the cylinder contains UF_6 vapor while the lower half contains the bulk of the solid UF_6. Initially, both the upper and lower cylinder wall temperatures increase rapidly, but the upper cylinder wall temperature increases faster than that of the lower section. The following observations from experimental studies describe UF_6 cylinder behavior during exposure to a fire:

- The upper cylinder wall temperature increases rapidly due to the low thermal capacity and thermal conductivity of the UF_6 vapor
- There is a radiant heat transfer of energy from the upper cylinder wall to UF_6 resulting in melting of UF_6 at the surface.
- Liquid UF_6 forms a stable liquid stratified layer at the UF_6 surface dividing the cylinder into two sections (thus it is reasonable to analyze the top and bottom sections separately*)*
- There is a continuous transfer of heat and mass across the liquid surface between the UF_6 liquid and vapor regimes (through *evaporation and condensation*)
- The UF_6 contacting the lower cylinder wall starts to melt creating a liquid regime between the cylinder wall and UF_6 solid.

As the temperature of the heating surface is increased, a point is reached where, in certain places, the energy level of the liquid adjacent to the surface becomes so high that some of the molecules break away from the surrounding molecules, are transformed from liquid into a vapor nucleus, and finally form a vapor bubble *(*"Principle of Heat Transfer," by Frank Kreith)

- Initially, the solid UF_6 remains in the middle of the cylinder surrounded by liquid regime supported by the two convex cylinder ends (this is an interpretation of the experimental data, rather than an observation).
- At some point, the solid UF_6 moves downward pushing the liquid upward (*sinking of solid core*). The condition of this movement may be due to a breaking of the solid into few blocks or melting of the end sections to cause the solid block to slide along the end wall.
- With the onset of the liquid UF_6 boiling in the lower section of the cylinder, the temperature of the lower cylinder wall decreases dramatically. This creates a large temperature difference around the cylinder wall (a temperature gradient), about 400° ~ 500° C, from the top to the bottom of the cylinder
- The temperature of the lower section increases slowly while the solid UF_6 remains in the cylinder and continues melting.

2. Description of Tenerife Program

The Tenerife program conducted six tests. The following is a description of the tests. Table 3 provides a matrix of the key points of these tests.

Test Number 1

An empty cylinder was heated to an 800° C fire condition to calibrate the sensors.

Test Number 2

The test cylinder contained 4,447 Kg of depleted UF_6. There were actually two tests with this cylinder, *i.e.*, the cylinder was heated twice to 800° C. The first heating lasted 10 minutes, followed by 10 days of cooling. The second heating was scheduled for 20 minutes but was shut down at 18 minutes because of a rapid increase in the cylinder pressure. The cylinder pressure at shut down was about 20 bar.

Test Number 3

A test cylinder containing 4,353 Kg of UF_6 was heated to an 800° C fire condition for one minute and 24 seconds before shutting down due to an electrical problem.

Test Number 4

A test cylinder containing 4,445 Kg was heated to an 800° C fire condition for 19 minutes and 35 seconds. The pressure recorded at shut down was 6.5 bar.

Test Number 5

A test cylinder containing 4,432 Kg was heated to an 800° C fire condition for 24 minutes. Both ends of the test cylinder were capped with a heat protective device. The pressure measured at shut down was 0.5 bar.

Test Number 6

A test cylinder containing 4,535 Kg of UF_6 was heated to **880° C** (compared to 800° C for the previous tests) for 18 minutes. The pressure at shut down was 2.5 bar.

The second heating of the Test Number 2 cylinder was terminated at 18 minutes due to a pre-determined safety condition, i.e., a rapid increase of pressure. Since the cylinder was heated once and cooled for 10 days (a portion of the solid was melted and frozen again), the UF_6 structure in the cylinder was not same as that in the other tests. The difference in the UF_6 structure in the test number 2 cylinder may be the reason for the rapid increase in the pressure during the second heating. Because the data from Test Number 2 represents an unrealistic phenomenon, it was not used in this study. In normal operations, were a cylinder ever heated to 800° C (an unlikely event, in the first place), it would be withdrawn from service and therefore removed from the normal and hypothetical risks of transportation.

Table 3 – Key Features of Tenerife Tests

Test	Weight (Kg) of UF_6	Maximum Temp. C	Time (min.)	Reason for Shut-Down	Cylinder pressure at Shut-Down (Bar)	Notes/Off-Normal Conditions
1	Empty	800° C	N/A	N/A	N/A	Testing sensors only
2A	4,447	800° C	10	Note 1	~0.5	Cooled 10 days before reheated for test 2B
2B	4,447	800° C	18	Note 2	20	Structure of UF_6 changed from previous heating, then cooling of cylinder. Rapid increase in cylinder pressure; intentional shut down
3	4,353	800° C	1.4	Electrical problem	N/A	Normal shut down
4	4,445	800° C	19.5	Note 2	6.5	N/A
5	4,432	800° C	24	Note 3	0.5	Heat-protective caps on ends of cylinder
6	4,535	**880°** C	18	Note 2	2.5	Temperature higher than regulatory test.

Notes:

1. Pre-determined test program
2. Shut down criteria of the program for safety concerns determined from the rate of increase in temperature, pressure and power consumption.
3. Cylinder heating was stopped after 38 seconds, due to defect in one furnace. After two days of delay, the heating resumed without the one-zone heater and was shut down, following the normal procedure.

3. Description of Cylinders used in ORGDP Rupture Test

A model 8A is an 8-inch diameter, 255 lb. capacity, cylinder constructed with Monel. Model 48X and 48Y cylinders are 10- and 14-ton capacity cylinders made of A-516 steel. A model 48G is a 14-ton capacity cylinder made of either A-285 or A-516 steel, depending on the date of manufacture. A model 48OM cylinder is an earlier design similar to the Model 48G cylinder

- The differences in the cylinder properties, which are relevant to the thermal analysis, are the size, the cylinder wall thickness, the material of the cylinder wall, and the ratio of the content to heat transfer area. There are some differences in the strength of the material between the A-516 and A-285 steel and among the different grades. However, the major difference in the 48-inch diameter cylinders is the cylinder wall thickness. A quick review of the differences in the physical strength of the steel is shown below. (The range in the values is due to the difference in grades, which is based on the carbon concentration.)

	A-285	A-516
Tensile stress in psi	45,000 ~ 75,000	55,000 ~ 90,000
Yield stress in psi	24,000 ~ 30,000	30,000 ~ 38,000

4. Description of Williams work

Reid Williams developed a lumped-parameter model in association with the IAEA cylinder project.[1] The model is constructed based on five masses; solid UF_6, vapor UF_6, liquid UF_6, cylinder wall contacting liquid UF_6, and cylinder wall contacting vapor UF_6. The model calculated the energy balance between the masses and determined the temperatures and pressure of each mass. The method lacked the details of the local heat and mass transfer phenomenon and structural analysis. The model predicted all the 48-inch diameter cylinders to rupture within 30 minutes in an 800° C fire. This is a crude model simulating the general behavior of the UF_6 evolution in a cylinder in a fire, but is not capable of predicting the cylinder rupture time with a reasonable accuracy.

[1] "Estimation of time to rupture in a fire using 6FIRE, a lumped parameter UF_6 cylinder transient heat transfer/stress analysis model," Third International Uranium Hexafluoride Conference. Paducah, KY. 1995

5. Methodological Issues

This analysis was based on a simplified model that focused on two sections of the cylinder, *i.e.*, the upper section containing mostly vapor and the lower section containing the bulk of solid UF_6. A simplified model was used instead of a full-scale model primarily because constructing a full-scale model would have taken an unreasonable amount of time and effort, given the deadlines for this report. However, there is no guarantee that a full-scale model would be any better than the others already existing, due to the complexity of the subject matter and a lack of credible data to validate the model. In light of the variations of temperature and pressure during the UF_6 evolution in a cylinder, any new model would not be fully validated and would be subject to criticism.

From the beginning of the study, it was assumed that a filled 48-inch diameter cylinder in the 30 minute, 800° C fire would not rupture from the hydraulic pressure of UF_6 expansion. It was also observed from the Tenerife data that the lower half of the cylinder would not rupture. One possible mode of the cylinder rupture would occur at the top of the cylinder wall, where the temperature is the highest. Measurements of the cylinder pressure agree well with the saturation pressure of the liquid UF_6 at the liquid surface. Hence, the simplified model keeps track of the cylinder temperature at the top of the cylinder, along with the cylinder pressure, for a possible cylinder rupture by hoop stress failure. The simplified model, which was validated with Ten4 data, calculates the temperatures and pressure beyond the Ten4 data range of 19.5 minutes. Given the short time, *i.e.*, 4-5 minutes, that the cylinder temperatures and pressure are calculated beyond the Ten4 data range, the extrapolation is justified. It is also reasonable to assume that there is no internal/external factor that would cause drastic changes in the UF_6 evolution process during the short period beyond the end of 19.5 minute timeframe.

6. Complexities of UF_6 behavior.

There is a continuous exchange of the heat and mass across the liquid surface between the UF_6 liquid and vapor regimes. This is a normal phenomenon of UF_6 trying to establish phase equilibrium. However, liquid and vapor temperatures are changing continuously and are in transient; determining the evaporation/condensation rate accurately is not possible. Additionally, the liquid surface temperature is not uniform along the surface, which results in different rates of the heat and mass exchange along the liquid surface.

When a cylinder is exposed to a fire, the cylinder wall temperature contacting the solid UF_6 increases rapidly due to the low thermal conductivity of the solid UF_6. When the wall temperature reaches the triple point of UF_6, the UF_6 starts to melt creating a liquid regime between the cylinder wall and the solid. At a certain point, liquid UF_6 starts to boil, extracting energy from the cylinder wall and resulting in a sharp decrease in the cylinder wall temperature. The condition for the onset of the boiling depends on the excess temperature (temperature difference above the boiling point of liquid) and the local liquid pressure. Since the temperature varies along the cylinder wall and continuous melting of UF_6, it is impossible to model the local liquid temperature and pressure to predict the onset of the boiling.

There is continuous melting of UF_6, along with the increase in the liquid UF_6, in the lower section of the cylinder. However, it is difficult to quantify the melting rate due to the varying cylinder wall temperature and upward flow of liquid UF_6. This becomes more complicated when the solid UF_6 sinks to the bottom of the cylinder pushing the liquid upward.

While this analysis shows results that are compatible with the Ten4 data, there is always room for further research. Additional studies on the complexities of UF_6 would provide a more thorough understanding of UF_6 behavior in the thermal environment.

7. Description of key terms and concepts used in the Report

Hoop stress failure

In a pipe or cylinder, there exist circumferential and axial stresses. The circumferential stress is also called hoop stress. When a cylinder or pipe is exposed to a pressure, both the hoop and axial stress are developed. When these stresses exceed the ultimate tensile stress of the material, there is breaking of the material. In a curved surface, the axial stress is one-half of the hoop stress. Hence, a pipe or cylinder exposed to a pressure would fail by hoop stress when the hoop stress exceeds the ultimate tensile stress.

Sinking of UF_6 core

This is a term expressing the movement of the UF_6 solid. In an early stage of a cylinder's exposure to a fire, a liquid regime is formed surrounding the solid UF_6. However, at some time later, the bulk of the solid UF_6 shifts downward, pushing the liquid upward. This is a geometrical problem and is difficult to model accurately and confidently. This phenomenon was theorized and was detected from the observation of the temperatures measured in experimental studies.

Stratification of liquid surface

Stratification of liquid surface is a layer of liquid surface at the top of solid UF_6 with a stable temperature gradient. Since the layer is thermally stable, there is no, or minimum, mixing of the liquid from the lower section of a cylinder.

Temperature gradient

This is a term expressing the temperature difference in cylinder shell developed by the difference in the heat transfer rate in the upper and lower sections of the cylinder.

Ultimate tensile stress

The ultimate strength of a material to tension force before breaking off the material is called the ultimate tensile stress. The ultimate tensile stress of a material varies with temperature. When a stress developed by a pressure is greater than the ultimate tensile stress, the material fails.