UF_6 Sample Package Development

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ABSTRACT

The United States Enrichment Corporation (USEC) developed the 2000 MED package that is designed to protect an ANSI N14.1 standard 1S sampling cylinder containing UF_6 enriched to a maximum 5% ^{235}U. The package was developed as a response to the new IAEA Safety Standards Series TS-R-1, "Regulations for the Safe Transport of Radioactive Material." With the new regulations, Competent Authority approval is now necessary for packaging of all shipments of uranium hexafluoride (UF_6), including small-volume samples. The globalization of the nuclear fuel industry, where uranium enrichment is often performed on the other side of the world from the next processing step, drives the need for this package.

Because there is such a limited quantity of UF_6 that can be carried within a sampling cylinder, the package meets the requirements of IAEA TS-R-1 for fissile-excepted material. The 2000 MED package fully complies with the TS-R-1 requirements as a Type H(U) package for land, water, and air transport.

The 2000 MED packaging is functionally divided into two parts: (1) the impact-absorbing thermal protection provided by the 2000 MED overpack and (2) the containment vessel consisting of the sampling cylinder. The 2000 MED packaging allows the sampling cylinder to survive both the regulatory free drop test and subsequent fully engulfing fire test. The package's protective ability combined with a lightweight, easy opening design makes the 2000 MED a functionally efficient package.

The 2000 MED package was developed through a series of tests that included two full-scale fire tests. During packaging development, free drop testing was determined to have very little influence on the package design whereas thermal requirements controlled the design. Thermal protection had to be balanced against the need to keep the package as small as possible since it will be used in a laboratory environment and will be air transported. The resulting design allows easy access to the sampling cylinder, yet provides complete protection in an easy-to-handle package, shipped either as a single unit or in a multiple package configuration.

REGULATORY REQUIREMENTS

The IAEA Safety Standards Series TS-R-1 designates performance requirements regarding transportation of packages containing UF_6:

- ¶629 specifies that UF_6 shall be packaged and transported in accordance with the provisions of ISO 7195[1] and Paragraphs 630 and 631; ISO 7195 provides equivalent safety requirements to ANSI N14.1[2].
- ¶630(a) specifies that the package withstand without leakage and without unacceptable stress, as specified in ISO 7195, the structural test specified in ¶718, *i.e.*, 2.76 MPa (400 psig) internal pressure.

- ¶630(b) specifies that the package withstand without loss or dispersal of the UF_6 the test specified in ¶722, *i.e.*, a 1.2 meter (4.0 foot) free drop of the package onto a target so as to suffer the maximum damage with respect to the safety features to be tested.
- ¶630(c) specifies that the package withstand without rupture of the containment system the test specified in ¶728, *i.e.*, a thermal test at 800 ºC (1,475 ºF) for 30 minutes.
- ¶631 specifies that the package shall not have a pressure relief device.

Furthermore, since the 2000 MED package is designed to transport 400 grams maximum of UF_6 enriched to 5% ^{235}U maximum (*i.e.*, less than 15 grams of fissile material), it is fissile excepted in accordance with ¶672(a)(i) and additional regulatory tests are not required. Note that 450 grams of UF_6 enriched to 5% ^{235}U maximum corresponds to 15 grams of fissile material.

PACKAGE DESCRIPTION

As shown in Figure 1, the 2000 MED packaging is functionally divided into two parts: (1) the impact-absorbing thermal protection provided by the overpack and (2) the containment vessel consisting of the 1S sampling cylinder. Shielding is not required due to the self-shielding nature of UF_6. Fully loaded, the 2000 MED package weighs approximately 22.7 kg (50 lb).

The 2000 MED packaging is fabricated primarily of austenitic stainless steel and thermal insulation. In addition, silicone sponge rubber is used within the packaging's interior cavity for additional shock and thermal protection.

The 2000 MED package is designed to utilize a standard, 10-gallon, open-head, stainless steel drum. A standard bolted clamping ring secures the drum lid to the body. A combination of stainless steel sheet and light-duty pipe comprise the interior structure.

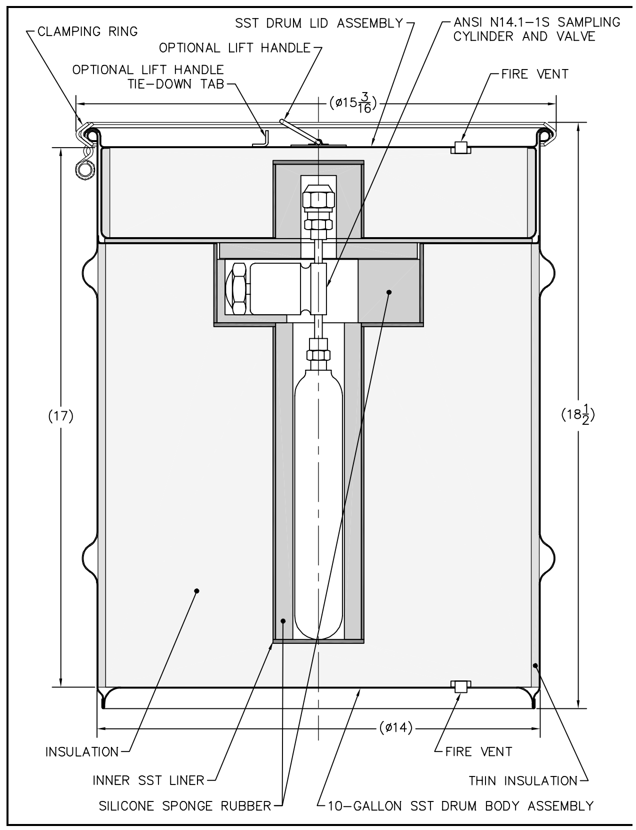

Figure 1, 2000 MED Package

The insulating materials have a primary function of providing thermal protection during the hypothetical accident condition (HAC) fire event and a secondary function of providing energy absorption during the normal conditions of transport (NCT) free drop event. The insulating material has low thermal conductivity, high-temperature stability and resistance to vibration and chemical deterioration. The thin insulating material serves as a compatible material to the main insulating material, and is used to eliminate some of the "rattle" space between the main insulating material and drum wall. All insulating material is sealed within the stainless steel shells.

Two removable plastic pipe plugs (one each in the lid and drum) serve as fire vents. The fire vents soften and melt quickly when exposed to fire temperatures. These two vents allow for release of air and outgas products released from the insulating material during heat-up.

As delineated in ISO 7195 and ANSI N14.1, the 1S sampling cylinder is fabricated entirely of ASTM B162 nickel or ASTM B127 Monel. A valve is threaded into the end of the sampling cylinder affecting its closure, and is fabricated of ASTM B164 Monel. The sampling cylinder and valve assembly is fully protected within the 2000 MED packaging.

PACKAGE TEST PROGRAM

Two 2000 MED test units were used for certification testing: (1) an Engineering Test Unit (ETU) to determine overall design acceptability and (2) a Certification Test Unit (CTU). Except for some minor design modifications to the CTU after ETU testing, both test units were identical.

The purpose of packaging testing was to demonstrate compliance with the requirements of ¶630(b) and ¶630(c) of TS-R-1. Test acceptance criteria were to demonstrate that the sampling cylinder did not leak and the calculated pressure would not have ruptured the cylinder following free drop and fire testing. The requirements of ¶630(a) were met by acquiring a sampling cylinder certified to meet the requirements of ANSI N14.1.

The NCT free drop testing was performed at Southwest Research Institute's facilities in San Antonio, Texas. An M/RAD Model 3636 (200) DT package drop tester, with a 90.7 kg (200 pound) maximum lift capacity, a 91.4 cm (36 inch) cube bulk capacity and an adjustable drop test height of 30.5 to 152.4 cm (12 to 60 inch) was used as the release mechanism for the NCT free drops. The package drop tester's steel base was anchored to a heavy concrete floor. Two bounding free drops were performed on each test unit:

- As illustrated in Figure 2a, the NCT center of gravity over corner free drop test provided the greatest likelihood for causing release of the drum lid. The lid's release would result in exposing the cylinder to the direct effects of the HAC fire event and that could result in rupture of the cylinder. By orienting the clamping ring bolt to align with the impact surface, the corner drop potentially caused the most damage to the package by concentrating all of the kinetic energy of the free drop on the clamping ring bolt region. The corner drop further challenged the clamping ring due to the substantial thrust load applied to the drum lid.
- As illustrated in Figure 2b, the slapdown free drop test provided the greatest likelihood for high lateral shear and bending forces in the valve-to-cylinder fittings, leading to a potential cylinder leak. By orienting the clamping ring bolt to align with the impact surface, the slapdown drop potentially caused the most damage to the sampling cylinder assembly by concentrating much of the kinetic energy of the slapdown drop on the previously damaged clamping ring bolt region and correspondingly into the valve-to-cylinder connection. Orienting the valve assembly downward ensured that the maximum lateral shear and bending forces were applied.

HAC fire testing was performed at Southwest Research Institute's remote test facility located in Sabinal, Texas (approximately 60 miles west of San Antonio). Operated by the Department of Fire Technology, the facility's mobile technical support trailer used a portable computer and digital data acquisition system to record test temperatures and weather conditions. The fire test facility used a cooled, tubular steel structure at the center of the fuel pool to support the test unit. The steel structure supports a test unit from 0.6 to 1.0 meters (up to 40 inches) above the pool surface. As illustrated in Figure 2c, vertical members supported the test item at the proper height and were located outside the footprint of the 2000 MED package. Horizontal members were configured to support the test item in a horizontal orientation.

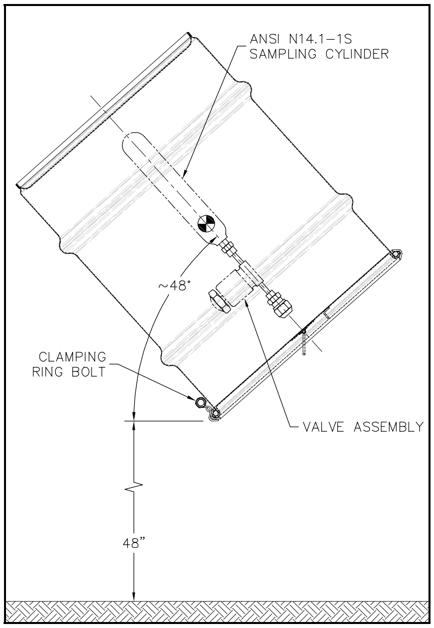

Figure 2a, Corner Drop Test

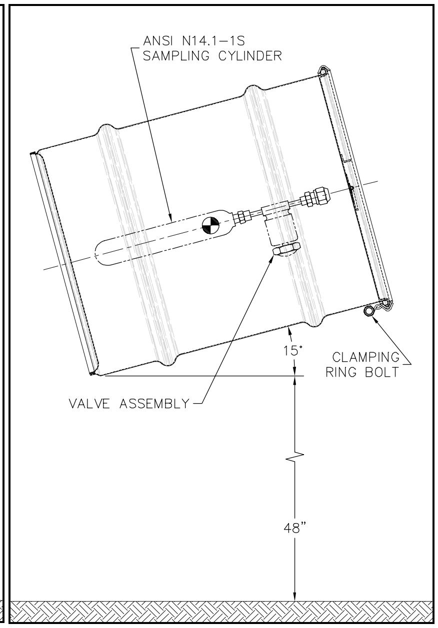

Figure 2b, Slapdown Drop Test

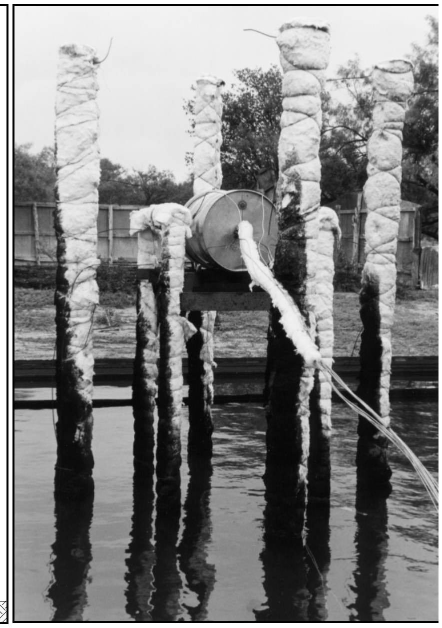

Figure 2c, Fire Test

The fire pool dimensions were 4.6 × 4.6 meters (15 × 15 feet) resulting in a nominal distance from the test item to the fire boundary of 2.3 meters (7½ feet), thus satisfying the 1 to 3 meter distance recommended in draft IAEA Safety Standards Series No. ST-2. Strategically placed thermocouple towers measured and recorded fire temperatures during the test. Jet-A fuel, a kerosene based petroleum product, was floated on water in the central tank to provide the engulfing flame. During CTU testing (but not ETU testing), the windward side of the pool was shielded by a 3.7 meter (12 foot) high windscreen deployed at a nominal 7.6 meter (25 foot) distance from the pool center. The windscreen was constructed of zinc plated, corrugated sheet steel resulting in a screen density of approximately 95%. Measured wind velocity at the center of the pool was reduced by a factor of 4 to 5.

To simulate the mass of the UF_6 during the NCT free drop tests and HAC fire test, the sampling cylinder was filled with 0.45 kg (0.992 pounds) of "fine" steel shot (*i.e.*, 1.0 mm (0.04 inch), or smaller). Using steel shot was reasonable because most carbon steels exhibit a specific heat of about 461 J/kg-ºC (0.11 Btu/lbm-ºF), and compare well with the specific heat of solid UF_6 of 477 J/kg-ºC (0.114 Btu/lbm-ºF); thus. A wire mesh screen was installed following installation of the steel shot to prevent fouling the valve during leak testing.

Temperature indicating labels were used on most internal surfaces and thermocouples were used at six locations on the exterior surfaces to measure the maximum test unit temperatures during the fire test for the ETU and CTU. In addition, the CTU fire test temperatures were monitored by using four thermocouples on the sampling cylinder and one on the valve assembly body. No other package instrumentation was used.

Prior to beginning each test series, the sampling cylinder was pressurized to 0.965 MPa (140 psig) and soap bubble tested. Pressurizing to 0.965 MPa (140 psig) ensured that at least 0.689 MPa (100 psig) minimum would be available for post-test pressure measurement and soap bubble testing. Furthermore, each test unit was preheated to a uniform temperature of 60 ºC (140 ºF), corresponding to the maximum calculated HAC pre-fire steady state temperature.

Results of ETU testing are summarized as follows:

- Corner drop damage was a 6.35 cm (2½ inch) wide flat at the clamping ring bolt, corresponding to a calculated crush depth of 0.16 cm (1/16 inch), and a small, inconsequential crack in the clamping ring.
- Slapdown drop damage was a 7.62 cm (3 inch) wide flat at the clamping ring bolt corresponding to a calculated crush depth of 0.40 cm (5/32 inch), and a 8.89 cm (3½ inch) wide flat at the drum bottom corresponding to a calculated crush depth of 0.56 cm (7/32 inch).
- Fire test flame density and coverage were consistently high throughout the duration of the fire, with occasional wind gusts as high as 5.1 m/s (11½ mph) temporarily uncovering the package during the fire (*i.e.*, typically with durations of 1 to 3 seconds). Fire duration was approximately 33 minutes. Considering wind speed and direction, the average package external surface temperature was 822 ºC (1,512 ºF). Flames were visible from the fire vents for approximately 11 minutes after fire cessation; all flames extinguished approximately 12 minutes after fire cessation (*i.e*., approximately 45 minutes following fire ignition).
- Following removal of the clamping ring and lid, bright blue and light blue discoloration of the internal lid surfaces indicated temperatures in excess of 343 ºC (650 ºF). Radially inward on these same surfaces, colors varied between straw and yellow, indicating temperatures in the 232 ºC (450 ºF) range. The silicone sponge rubber was gummy, but still intact. Because of these relatively high temperatures, all temperature indicating labels were either destroyed or had tripped at their maximum value. The sampling cylinder exhibited significant buildup of blackened deposits on the valve body, but not on the cylinder body. These deposits appeared to be offgas condensate, *i.e.,* materials that burned and vaporized within the sampling cylinder's cavity and condensed onto the coolest surface. The thermal insulation exhibited darkening at its outermost surfaces, most likely due to oxidation of the insulation's constituents.
- Successful post-test soap bubble leak testing was performed on the sampling cylinder, both before and after installing the same pressure measuring equipment and configuring it the same as pre-test leak testing. The internal pressure was measured to be 0.765 MPa (111 psig) for a sampling cylinder temperature of 36 ºC (97 ºF), or a pressure of 0.731 MPa (106 psig) when applying temperature correction to the pre-test sampling cylinder temperature of 23 ºC (74 ºF).
- All temperature indicating labels on the valve body were burned away, whereas the temperature indicating labels on the sampling cylinder were intact, but tripped at their maximum value. Because temperatures exceeded the temperature indicating label limits, the maximum pressure for UF_6 in the sampling cylinder could not be determined. Therefore, we repeated the test series with a second test unit (CTU), using thermocouples to monitor the sampling cylinder temperatures.

Although post-test leak testing was successful, determination of the maximum cylinder pressure was not possible because the cylinder temperature was not documented. Consequently, the use of thermocouples during CTU testing ensured that maximum temperatures would be obtained. To reduce heat transfer into the package's interior and reduce temperatures, the CTU design was slightly modified to include additional silicone sponge rubber between the drum lid and body.

Results of CTU testing are summarized as follows:

- Corner drop damage at the clamping ring bolt was negligible.

- Slapdown drop damage was conservatively magnified because improper release resulted in what was essentially a side drop test. The drop tester was reset and the slapdown drop test repeated. Total damage was a 8.89 - 10.16 cm (3½ - 4 inch) wide flat at the clamping ring bolt corresponding to a calculated crush depth of 0.56 - 0.71 cm (7/32 - 9/32 inch), and a 10.16 cm (4 inch) wide flat at the drum bottom corresponding to a calculated crush depth of 0.71 cm (9/32 inch). Note that this damage included the cumulative effects of the previous side drop test that produced a 6.35 - 7.62 cm (2½ - 3 inch) wide flat at the top and bottom.
- Fire test flame density and coverage were consistently high throughout the duration of the fire, with occasional wind gusts as high as 8½ mph; the presence of the high-density windscreen prevented uncovering the package during the fire. Fire duration was approximately 33 minutes. The average package external surface temperature was 1,019 ºC (1,867 ºF), or 197 ºC (355 ºF) hotter than the ETU fire test. While the windscreen was extremely effective in reducing wind speed over the pool, the high-density (*i.e.*, low porosity), close proximity (7.6 meters (25 feet) from the pool center), and high reflectivity (galvanized, corrugated steel sheet) were the most likely contributors to the significantly higher flame and package surface temperatures. Furthermore, the average flame temperature was 151 ºC (271 ºF) hotter than the ETU fire test. This extra-regulatory condition may have been the single biggest reason for the high temperatures recorded for the sampling cylinder. Flames were visible from the fire vents and lid gasket for approximately 11 minutes after fire cessation; all flames extinguished approximately 14 minutes after fire cessation (*i.e.*, approximately 50 minutes following fire ignition). The maximum temperature for the sampling cylinder body was 243 ºC (469 ºF), occurring 3 hours after fire ignition. Adjusting for the low start temperature at fire ignition (*i.e.*, 54 ºC (129 ºF) versus the target temperature of 60 ºC (140 ºF); ΔT = 6 ºC (11 ºF)) resulted in a maximum sampling cylinder temperature of 243 ºC + 6 ºC = 249 ºC (480 ºF).
- Following removal of the drum clamping ring and lid, the 0.95 cm (3/8 inch) thick silicone sponge rubber between the lid and body surfaces was completely charred. However, the underlying silicone sponge rubber in the sampling cylinder cavities was intact, although still gummy. The sampling cylinder exhibited significantly less buildup of blackened deposits on the valve body, but somewhat more on the cylinder body. Again, these deposits appeared to be offgas condensate – materials that burned and vaporized within the sampling cylinder's cavity and condensed onto the coolest surface. All temperature indicating labels on the cylinder and valve body were intact, displaying readings between 249 ºC and 260 ºC (480 ºF and 500 ºF). The thermal insulation exhibited significantly more darkening throughout its radial thickness than noted for the ETU, thereby providing further evidence that the CTU fire test was much hotter than the ETU fire test.
- The presence of the rigid thermocouple leads connected to the sampling cylinder made post-test removal extremely difficult, and several times the sampling cylinder was inadvertently jolted against the pavement. Following sampling cylinder removal, soap bubble leak testing showed a leak. To determine when the leak started, the internal pressure was measured to be 0.731 MPa (106 psig) at a sampling cylinder temperature of 33 ºC (91 ºF), or 0.710 MPa (103 psig) when applying a pre-test temperature correction of 23 ºC (74 ºF). Pressure loss from the sampling cylinder was recorded over a relatively long duration (0.097 MPa (14 psig) after 23½ hours). During the first 20 minutes, the pressure dropped 0.021 MPa (3 psig). Assuming the corrected pressure in the sampling cylinder had started at 0.731 MPa (106 psig) and that the sampling cylinder started leaking because of the excess jolting during disassembly, then a 0.021 MPa

(3 psig) loss over a 20 minute period is reasonable. Had the sampling cylinder started leaking either from the free drop tests two days earlier or fire test 12 hours earlier, the pressure in the sampling cylinder would have been at least 0.048 MPa (7 psig) lower than measured. Therefore, the observed leakage and 0.021 MPa (3 psig) loss of internal pressure was definitely caused by rough handling during the post-test disassembly process. The sampling cylinder had not leaked prior to that point in time.

- Based on a sampling cylinder temperature of 249 ºC (480 ºF), subsequent calculations determined an internal pressure of 21.56 MPa (3,127 psig) for a 400 gram loading of UF_6. Using a specified minimum wall thickness of 0.100 inches for the sampling cylinder, the rupture pressure was determined to be 54.17 MPa (7,857 psig). Thus, a relatively significant margin against cylinder rupture is demonstrated.

In conclusion, the CTU free drop and fire testing successfully demonstrated compliance with the requirements of ¶630(b) and ¶630(c), respectively, of IAEA Safety Standards Series TS-R-1.

FIRE TEST CONSERVATISM

The average temperature of the sampling cylinder from CTU fire testing was used as the basis for calibrating the 2000 MED package's material properties for the 5½ hour CTU fire event. An axisymmetric ANSYS finite element analysis model of the CTU was created that used identical external test conditions recorded during CTU fire testing (*i.e.*, flame temperature and fire duration). Adjusting the thermal insulation's material properties to account for temperature-dependent effects resulted in a nearly identical trace of average cylinder temperature versus time compared to the CTU fire test. Once the temperature correlation was established, a second analysis using external regulatory conditions (*i.e.*, a regulatory temperature of 800 ºC (1,475 ºF) and 30 minute fire duration) determined the CTU fire test's degree of conservatism.

Using regulatory requirements for the fire test conditions, the average sampling cylinder's temperature was reduced from the measured CTU fire test maximum of 243 ºC (469 ºF) to a regulatory calculated maximum of 174 ºC (345 ºF), for a total temperature reduction of 51 ºC (124 ºF). Figure 3 illustrates the comparison of average cylinder temperature versus time for both CTU fire testing and regulatory conditions, where zero time indicates fire ignition. The reasons for this significant reduction in cylinder temperature are twofold: (1) the duration of CTU fire testing exceeded regulatory requirements by three minutes (10%), and (2) measured ambient (flame) temperatures exceeded regulatory requirements by nearly 204 ºC (400 ºF) (~27%).

The corresponding pressure within the sampling cylinder is significantly reduced due to the 51 ºC (124 ºF) temperature reduction. The pressure reduced from 21.56 MPa (3,127 psig) for the CTU test temperature of 249 ºC (480 ºF) to 1.97 MPa (286 psig) for the regulatory calculated temperature of 180 ºC (356 ºF), including the 6 ºC (11 ºF) starting temperature adjustment. This reduction in temperature allows the stated UF_6 mass restriction of 400 grams to be increased to the ANSI N14.1 limit of 450 grams and the required minimum sampling cylinder wall thickness of 0.25 cm (0.100 inch) to be decreased to the ANSI N14.1 limit of 0.16 cm (0.0625 inch). With a payload mass of 450 grams UF_6 and a sampling cylinder wall thickness of 0.16 cm (0.0625 inch), the resulting pressure is 10.34 MPa (1,500 psig). This pressure is well below the sampling cylinder's calculated rupture pressure of 32.97 MPa (4,782 psig), thereby demonstrating full compliance with TS-R-1 requirements.

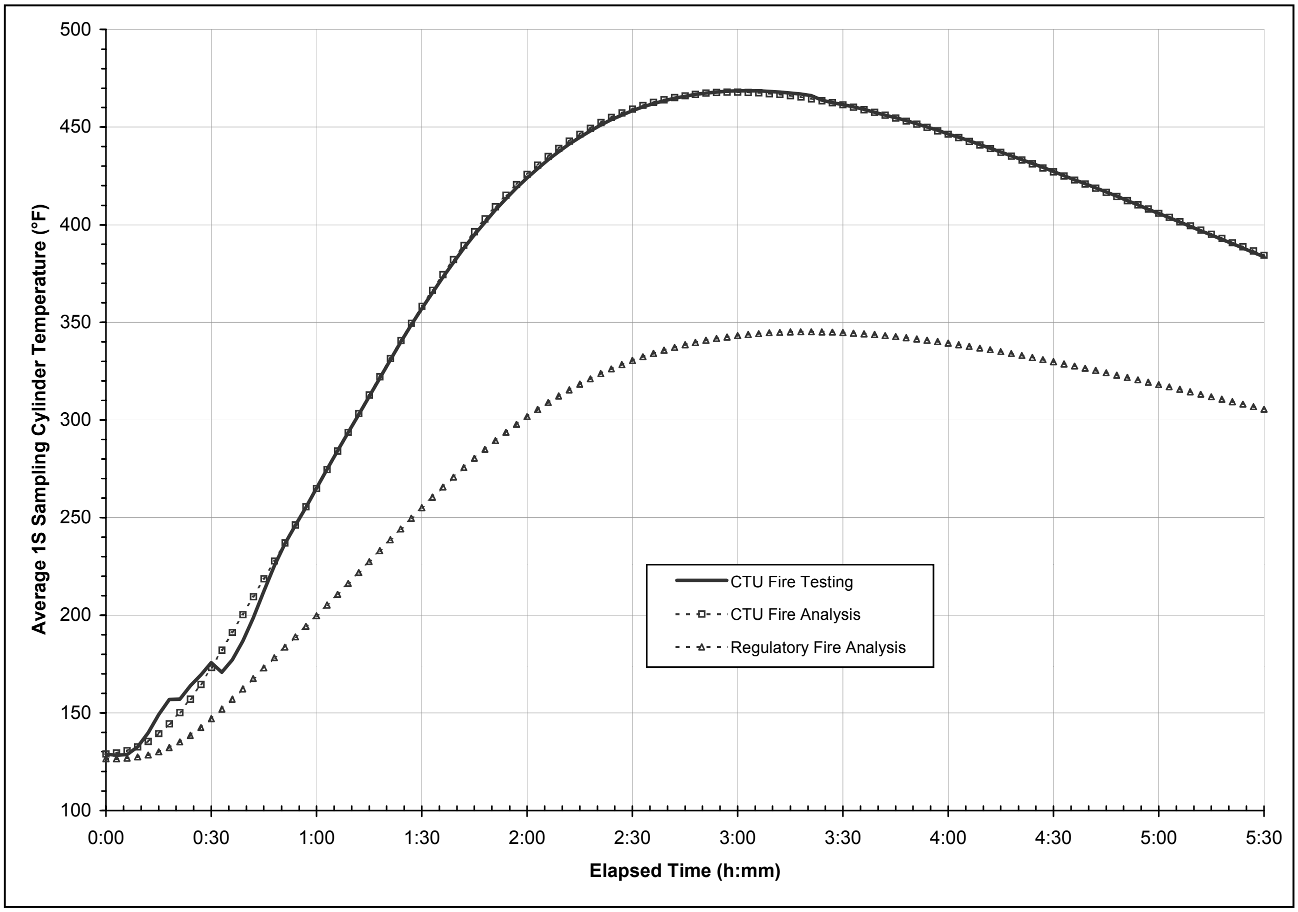

Figure 3, Comparison of CTU and Regulatory Fire Test Temperatures for the sampling Cylinder

REFERENCES

[1] ISO 7195-1993, *Packaging of Uranium Hexafluoride (UF_6) for Transport*, International Organization for Standardization, Case Postale 56, CH-1211 Genève 20, Switzerland, 1993.

[2] ANSI N14.1-1995, *American National Standard for Nuclear Materials – Uranium Hexafluoride – Packaging for Transport*, American National Standards Institute, Inc., New York, NY, 1995.

[3] IAEA, *Transport of Radioactive Material – Advisory Material for the Regulations for the Safe Transport of Radioactive Material (1996 Edition), Safety Standards Series No. ST-2*, *draft* 1996 Edition, International Atomic Energy Agency, Vienna, Austria.