TENERIFE Program: Thermophysical Behavior of UF_6 in a Transport Container Under Fire Conditions

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INTRODUCTION

The International Atomic Energy Agency, in accordance with the revision of the IAEA Regulations in 1996, has been working on establishing regulations for UF_6 transportation taking into account chemical and radiological hazards. Up to now, various experimental and computational extrapolations of the resistance of a UF_6 container under certain fire conditions have been discussed. However, among these results there is a great dispersion as the occurrence of rupture because of the scale effect (Williams 1988 ; Yamakawa and Shiomi 1988 ; Abe et al. 1989 ; Duret and Bonnard 1983 ; Duret and Warniez 1988). In order to make clear the thermophysical behavior of UF_6 in a transport container under realistic fire conditions, an experimental research program (TENERIFE) was defined and started in 1991 under the CRIEPI/IPSN joint research agreement (Casselman et al. 1992). The first objective is to qualify the computer codes. The second is to evaluate the behavior of a 48Y-container in a realistic fire condition. In this paper, the first test results of the TENERIFE program are presented.

FIRE TESTS

Description of Test Apparatus

Test equipment is composed of an experimental container, an electrical furnace, and a leaktight vessel as shown in Figure 1. This equipment is installed in a leaktight massive building in the IPSN facility for research on fires, in the Cadarache Research Center of CEA in France. In this building, the UF_6 recovery system is also installed considering the accidental rupture of the container with dispersion of UF_6 inside the leaktight vessel. The leaktight vessel is designed to maintain the furnace in vacuum condition (5Pa) and to confine UF_6 in the case of a container leakage.

The total electrical furnace power is 660kW to produce a rapid heat transient by radiation (increase to 800℃ during 4 minutes) with four heating zones. It is positioned horizontally inside the leaktight vessel.

The specification of the experimental container corresponds to a 48Y container described in ANSI N14-1 1990 except in length so that the thermal exchanges can be properly reproduced. The container is made of A516 grade 70 steel and shorter in length than a standard 48Y container (about 1/3) to limit the quantity of UF_6 to about 4 tons. This container is equipped with flanges for measurements (pressure, temperature, and UF_6 level) and valves for operations (filling, emptying, and cleaning of UF_6) and placed inside

the electrical furnace. Figure 2 shows the measurement position.
During a fire test, various experimental parameters (electrical power, strain and associated temperature on the container surface, UF_6 mass temperature, container pressure, furnace temperature, experimental vessel pressure and so on) are measured. These measurements are recorded by two identical acquisition stations. If a station unfortunately goes down, the other one automatically catches the tasks.
Principally, all operations during the test are controlled and monitored from the control desk in the operation room with the help of the supervision system. On the supervision system, all information of the test equipment (furnace power, pressure, temperature, strain, etc.) is displayed. Moreover, this system can detect defaults in the measurements and

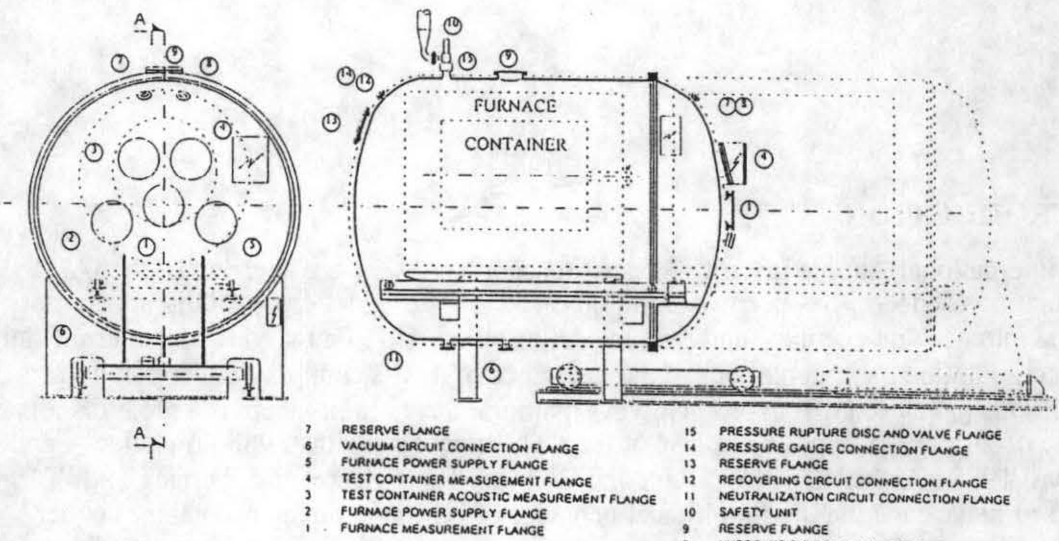

Figure 1. Disposition of the Test Apparatus (TENERIFE)

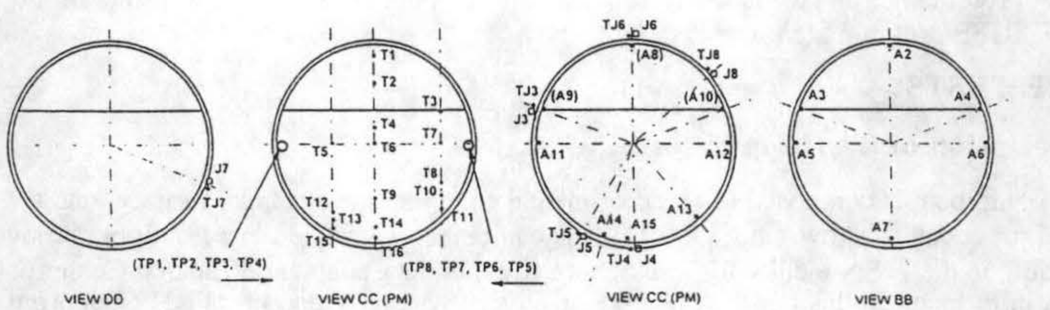

Figure 2. Instrumentation of the Experimental Container (TENERIFE)

decide the operation mode (normal, dangerous and stop) according to the flow chart related to the safety threshold values of the test parameter.

Test Matrix

The test matrix includes six tests as shown in Table 1. During the test, heating must be interrupted if pre-established thresholds are reached in items of strain and temperature on the container surface, temperature and volume expansion of UF_6, container internal pressure, and so on. Up to now, Test No. 1, No. 2, and No. 3 have been carried out. The test chronology and parameters for the following tests have been modified taking into account the results derived from the already performed tests.

Table 1. Test Matrix of the TENERIFE Program

Test No.	Furnace Temp. (°C)	Time Duration (minute)		Filling Mode	Purpose	Remarks
		Planned	Executed			
TEN1	800		6.5 15	Empty	* Qualification of heat flux from the furnace to the container	Executed in September '95
TEN2	800 800 800	10 20 $X^{1)}$	10 18 ----	Liquid	* Safety approach by increasing the heating time duration * Investigation of the general behavior of the test container * Verification of numerical model	Executed in June '95 Executed in July '95
TEN3	800	18	1.4	Liquid	* Realistic fire test	Executed in October '95 but failed and postponed
TEN4	800	18		Liquid	* Re-execution of TEN3	Planned in February '96
TEN5	800	18		Liquid	* Analysis of the end effect on a container with heat covers	Planned in January '96
TEN6	>800	$Y^{1)}$		-----[2)]	* Analysis of filling mode or Effect of heat flux in conformity with IAEA specifications	Planned in March '96

1) X and Y designate the termination time when the test parameters reach the pre-established threshold values.
2) Not decided

Test No. TEN1 : Calibration Test

A calibration test was performed to quantify as precisely as possible the heat flux delivered by the furnace to the container with an empty cylinder. From the temperature of each thermocouple, the heat flux at the point P is given by equation (1)

$$F_P = \rho * C_P (T_P) * D * dT_P /dt \quad \text{------------} \quad (1)$$

where

F_P : Local heat flux at the point P C_P: Steel thermal capacity (which depends on T_P)
T_P : Steel temperature at the point P ρ : Steel density D : Steel thickness

On the other hand, the external heat flux can be rewritten by equation (2).

$$F_P = E_{eq} * \sigma * [(T_F + 273)^4 - (T_P + 273)^4] \quad \text{------------} \quad (2)$$

where

T_F : Furnace regulation temperature σ : Stefan-Boltzmann's constant
E_{eq}: Equivalent emissivity

Thus, equivalent emissivity can be adjusted to reproduce the measured heat flux. It is well known that the emissivity factor depends on the state of the surface, the existence of the paint, and the temperature. So, in this test, several heating phases were executed.

Test No. TEN2

Test No. 2 was considered as a safety approach. In the beginning, three separate heating phases with increasing duration had been provided. The first and second phases were executed to investigate the general behavior of the test container related to safety. In these tests, the time duration of exposure to high temperature (total surface heating at 800℃) was increased with special attention paid to "overshoot" effect after the heating operation. Actually, in the second phase, the electrical furnace was interrupted after 18 minutes manually because of the rapid rise of the container pressure. For safety reasons, the final heating phase was cancelled.

Test No. TEN3

Test No. 3 had been provided to verify the numerical model under realistic initial transport conditions and furnace temperature at 800℃. The heating time duration had been set to 18 minutes determined from Test No. TEN2 results. Unfortunately, during this test, the electrical furnace was automatically stopped by the request of the electrical protection system after 83 seconds heating. So, this test is postponed until later.

Test No.TEN4

This test includes the same test conditions as Test No. TEN3 to re-execute the realistic fire test. Therefore, the heating time duration will be set to 18 minutes with the surface heating 800℃ considering the Test No. TEN2 results.

Test No. TEN5

In this test, the end effect on a container equipped with heat covers will be investigated. This cover protects both ends of the container on a limited length. The test container will be exposed to total surface heating at 800℃. The initial distribution of the UF_6 inside the container will be investigated by gammagraphy prior to the test. The heating operations will be continued for 18 minutes determined from Test No. TEN2 results.

Test No. TEN6

In this test, two options are considered. One is to simulate a heat flux meeting the IAEA specifications, in other words, a temperature of 800℃, a flame emissivity of 0.9, and a container-absorbing capacity of 0.8.

Table 2 shows the comparison of the specification between IAEA and TENERIFE test conditions. The heat flux proposed by IAEA is equal to 55kW/m^2 when the steel temperature is 20℃. On the other hand, in the TENERIFE program, the heat flux between 40 and 51kW/m^2 can be achieved. Therefore, to satisfy the similarity between IAEA and TENERIFE, increasing the heat flux from the furnace must be provided. This is accomplished by regulating the temperature of the heating element of the furnace beyond 800℃ in relation to the average temperature of the steel.

Table 2. Comparison between TENERIFE and IAEA Conditions

ITEM	IAEA	TENERIFE
External temperature	800°C	800°C
External emissivity	0.9	0.8
Steel emissivity	0.8	between 0.6 and 0.8
Heating surface area	17.8 m^2	13.4 m^2
Heated surface area	17.8 m^2	6.6 m^2
Heat flux received		
if T_{steel} = 20°C	55 kW/m^2	40-51 kW/m^2
if T_{steel} = 500°C	40 kW/m^2	29-38 kW/m^2

The other is to investigate the effect of UF_6 container filling mode. This test is useful from the point of view of physical phenomena because the initial distribution of the UF_6 inside the container is no longer the same. The test container will be filled with the UF_6 in the gaseous phase and this filling mode concerns just over 3% of 48Y-cylinders and does not seem such an exceptional procedure. This container will be exposed to total surface heating at 800℃. The test parameters will be decided considering all of the previous test results. The heating operation will be continued during a time Y when one of the test parameters reaches the pre-established threshold values.

STATUS OF THE WORK AND FIRST RESULTS

Up to now, Tests No. TEN1, TEN2, and TEN3 have been performed. During Test No. TEN3, the furnace was automatically stopped by the request of the electrical protection system after 83 seconds heating. So, the test results of No. TEN3 are not presented in this paper.

TEST No. TEN1 : Calibration Test

Table 3 shows the test conditions of the Test No. TEN1.
First, in December 1994, several tests were performed to quantify the external heat flux delivered by the furnace with a painted container empty of UF_6 and verify the functions of the whole assembled system. The test results were satisfactory. However, it was found that the volatile products coming from the overheated paint could degrade the capacity of the isolation of the electrical furnace. As a result, to avoid any pollution of the furnace, paintings were removed from the test container by the sand-blasting method before tests.

Table 3. Test Condition of the Calibration Test

Test No.	Furnace Temp. (°C)	Max. Time Duration (minute)	Max. Container Temp. (°C)	Painting Color	Purpose	Date
TEN1-1	800	30	300	Silver	* Verify the operation of furnace	94-12-5
TEN1-1'	800	30	300	Silver	* Verify the cooling duration	94-12-7
TEN1-1"	800	30	300	Silver	* Evaluate the external heat flux and	94-12-9
TEN1-2	800	30	500	Silver	the influence of painting	94-12-15
TEN1-2'	800	30	500	Silver		94-12-16
TEN1-3	800	30	300	None	* Evaluate the external heat flux	95-9-15
TEN1-4	800	30	600	None		95-9-19

Second, in September of 1995, other tests were performed with an unpainted container to determine the heat flux and the equivalent emissivity factor in this condition. In order to compare the heat flow in the TENERIFE experiment, the equivalent furnace temperature supposing the IAEA condition is evaluated. In other words, if the external emissivity and the wall emissivity are assumed to be 0.9 and 0.8, respectively, the equivalent furnace temperature can be calculated by equation (2). Figure 3 shows the comparison between the experimental furnace temperature and the calculated values. According to these results, it was found that the calculated equivalent values were a little higher than 800℃. Therefore, the emissivity

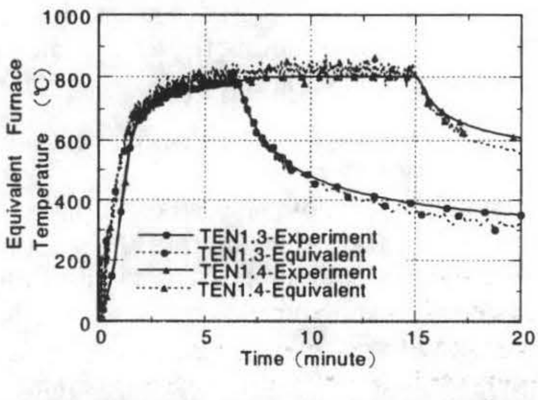

Figure 3. Comparison between the Experimental Furnace Temperature and the Calculated Values

factor of the sand-blasted steel is still under investigation.

TEST No. TEN2 : First Test with UF_6

During June and July of 1995, the first and second heating phases were performed with an unpainted container filled with UF_6 (4450kg). In these cases, the furnace temperature 800 ℃ was obtained in less than 4 minutes with an initial absolute pressure in the experimental vessel of 5 Pa. In the second phase, the heating was interrupted after 18 minutes because of the rapid rise of the container pressure. For safety reasons, the final heating phase was cancelled.

Test No. TEN2.1

This test was performed on June 28 1995. The heating duration (electrical power in operation) was 10 minutes and the initial UF_6 temperature was the room temperature (25 ℃). Some of the typical evolutions of pressure and temperatures are shown in Figure 4.

The principal results are summarized as follows.
Container Temperature
During the 10 minutes heating, the container temperature rose uniformly up to 350℃. During 2 minutes after the interruption of the electrical furnace, the lower part of the container (for example, at the point A12, A15) contacted with liquid UF_6 and was cooled down immediately.
UF_6 Temperature
In general, the UF_6 temperature reached the triple point temperature (about 64℃) after the interruption of the electrical furnace. Especially during heating near the container wall (for example, at the point T11) UF_6 temperature rose up to 160℃ because of the local fusion.
Container Pressure
During the heating, the container pressure rose up to 0.5bar. After the interruption of the electrical furnace, the pressure continued rising up to the triple point pressure (about 1.5bar).

Test No. TEN2.2

This test was performed on July 6 1995, continuously with the same container which had been submitted to Test No. 2.1 after cooling it to 35℃. This test was interrupted after 18 minutes because of the pressure increase inside the container. Leaktightness of the container was verified during the test. Some of the typical evolutions of pressure and temperature are shown in Figure 5.

The principal results are summarized as follows.
Container Temperature
After the interruption of the electrical furnace, the upper part of the container (for example at the point A8) was heated up to 530℃. On the other hand, the lower part (for example at the point A12, A15) was heated up to 280℃, and as soon as it contacted with the UF_6 liquid, the container temperature was cooled down immediately.
UF_6 Temperature
When the container pressure reached to 30bar, the lower part of the UF_6 mass (for example, at the point T11) remained in the solid state. On the other hand, the upper part of the UF_6 mass (for example, at the point T3) was in the liquid state and heated above 150 ℃. The maximum liquid surface temperature extrapolated by the adjusted container pressure considering the difference between two container pressure gauges seems to be 200℃ as shown in Figure 6.

Container Pressure
After 18 minutes heating, the container pressure was still about 12bar. However, as the slope of the container pressure seemed to be very high, the electrical furnace was interrupted manually. After that, the container pressure continued rising to a pressure near 30bar.

DISCUSSION

It can be considered that during Test No. 2.2 an important phenomenon of pressure increase appears after 15 minutes and the pressure goes on rising during 20 minutes after the interruption of the electrical heating up to a maximum pressure near 30 bar.

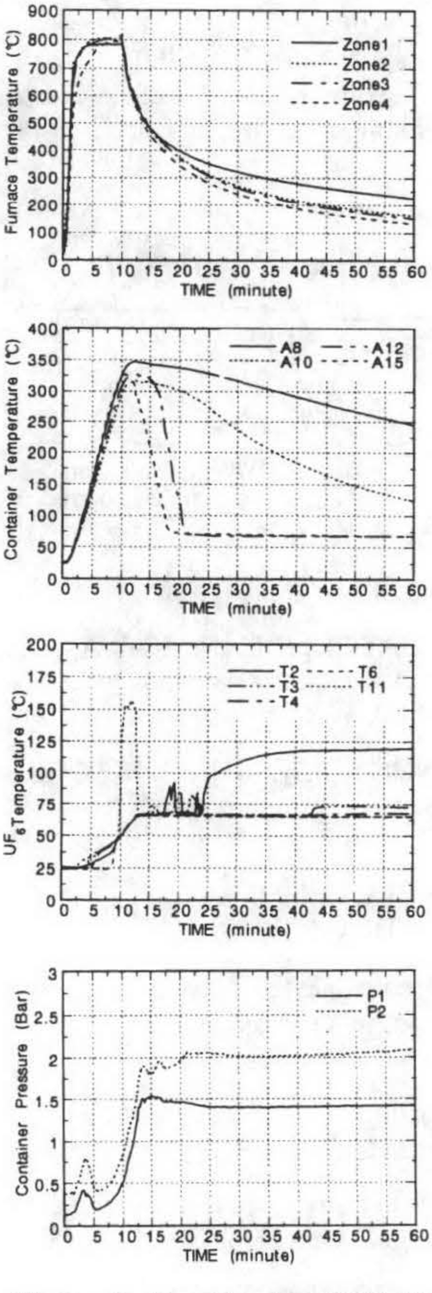

Figure 4. Test Results of TEN2.1
(800℃, 10 minutes)

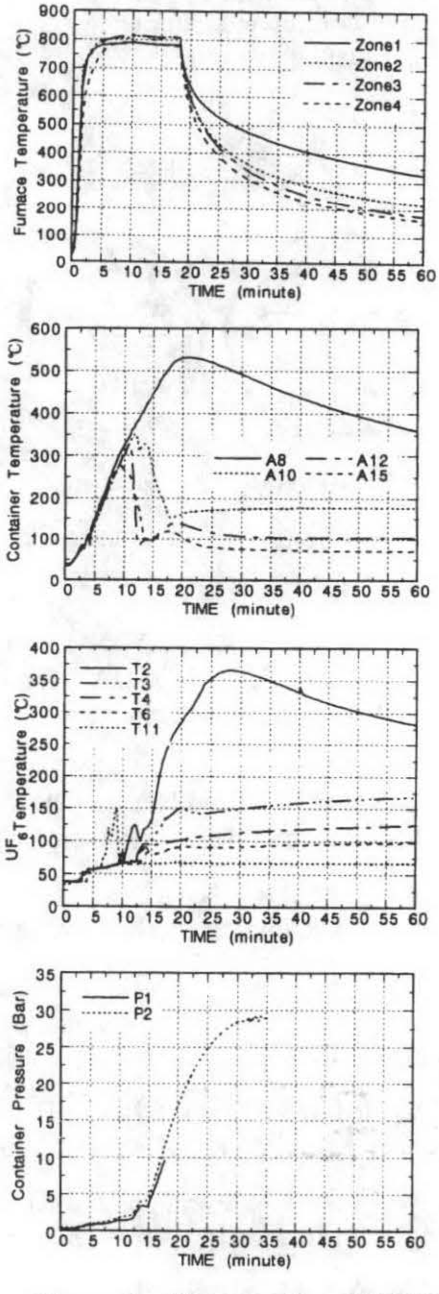

Figure 5. Test Results of TEN2.2
(800℃, 18 minutes)

Moreover, at that time, according to the temperature distribution of the UF_6 mass, the UF_6 solid and liquid existed together. The estimated state of UF_6 mass during Test No. 2.2 can be shown in Figure 7 (Pinton et al. 1995). So, to make clear the thermophysical behavior of UF_6, the mechanism of the break of the UF_6 coating and the heat exchange including the boiling and natural convection must be examined.

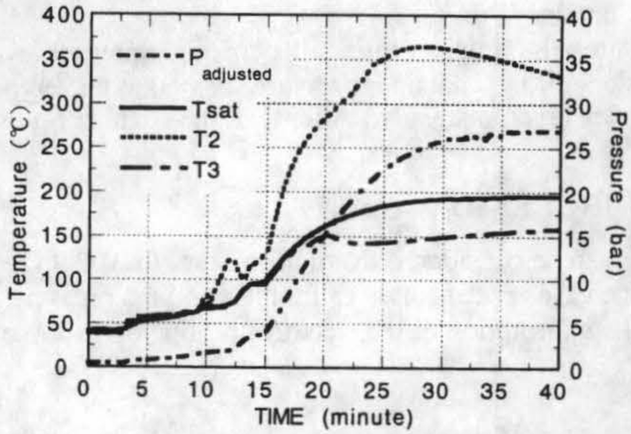

Figure 6. Maximum Liquid Surface Temperature Extrapolated by the Container Pressure

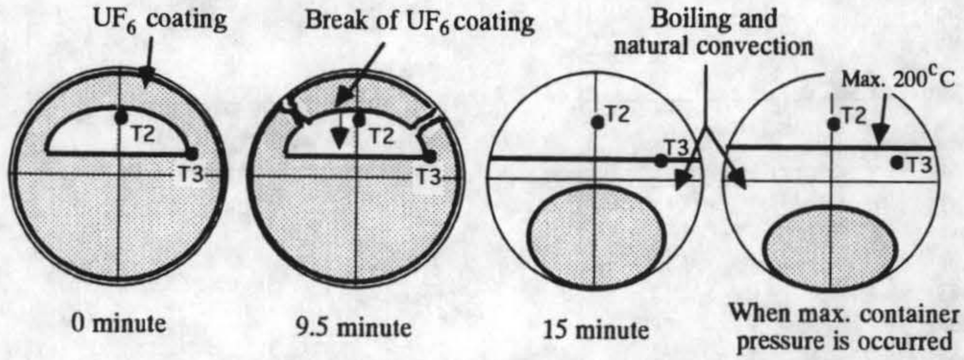

Figure 7. Estimated State of UF_6 Mass during Test No. 2.2

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