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INVESTIGATION OF UF_6 BEHAVIOR IN A FIRE[1]

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ABSTRACT

Reactions between UF_6 and combustible gases and the potential for UF_6-filled cylinders to rupture when exposed to fire are addressed. Although the absence of kinetic data prevents specific identification and quantification of the chemical species formed, potential reaction products resulting from the release of UF_6 into a fire include UF_4, UO_2F_2, HF, C, CF_4, COF_2, and short chain, fluorinated or partially fluorinated hydrocarbons. Such a release adds energy to a fire relative to normal combustion reactions. Time intervals to an assumed point of rupture for UF_6-filled cylinders exposed to fire are estimated conservatively. Several related studies are also summarized, including a test series in which small UF_6-filled cylinders were immersed in fire resulting in valve failures and explosive ruptures. It is concluded that all sizes of UF_6 cylinders currently in use may rupture within 30 min when totally immersed in a fire. For cylinders adjacent to fires, rupture of the larger cylinders appears much less likely.

NOMENCLATURE

A	-	area, ft^2
E	-	total heat requirements for heating a cylinder and UF_6 from initial to final conditions, Btu
F	-	view factor
ΔH	-	enthalpy change from initial to final conditions, Btu/lb
P	-	pressure, psia
q_2	-	heat flux relative to the cylinder surface area, $Btu/h \cdot ft^2$
Q	-	heat rate, Btu/h
r	-	cylinder radius, in
t	-	wall thickness, in
T	-	absolute temperature, °R
ϵ	-	emissivity
σ	-	Stefan-Boltzman constant
	-	0.173×10^{-8} $Btu/h \cdot ft^2 \cdot {}^\circ R^4$
σ_u	-	ultimate stress, psia
τ	-	time to rupture, min
1,2	-	subscripts denoting fire and cylinder, respectively

INTRODUCTION AND SUMMARY

In 1985, the Nuclear Regulatory Commission (NRC) requested that consideration be given to several UF_6-fire issues as a part of an ongoing program to develop an Accident Analysis Handbook. The issues concern (I) the reactions occurring between UF_6 released into a fire and combustible gases and combustion products and (II) the potential for UF_6-filled cylinders to rupture when exposed to fire. The results presented in this paper represent the current status of investigation into these issues.

Potential reaction products resulting from the release of UF_6 into a fire include UF_4, UO_2F_2, HF, C, CF_4, COF_2, and short chain, fluorinated or partially fluorinated hydrocarbons. UF_6 reactions with combustible gases add energy to a fire relative to normal combustion reactions with O_2. However, energy release appears to be maximized by the complete combustion of hydrocarbons to H_2O and CO_2 along with the complete hydrolysis of UF_6 by H_2O. The absence of kinetic data precludes identification of the most likely chemical species resulting from the release of UF_6 into a fire or, consequently, the corresponding energy increase. The development of appropriate kinetic data would require a substantial experimental program.

Time intervals to an assumed point of rupture for UF_6-filled cylinders (liquid UF_6 at 300°F) exposed to fire have been estimated in what should be considered conservative, preliminary calculations. Consideration was given to cylinders fully immersed in a fire and to those adjacent to a fire. Fire conditions utilized in the analyses encompass NRC criteria and a proposed ASTM standard. Several related studies are summarized, including a series of tests in which small UF_6-filled cylinders (corresponding to 5A- and 8A-sized cylinders) were immersed in fire resulting in valve failures and explosive ruptures. It appears reasonable to conclude that all sizes of UF_6 cylinders currently in use may rupture within 30 min when totally immersed in a fire; in some cases, there may be

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insufficient time to begin fighting a fire before rupture occurs. For cylinders adjacent to fires, rupture of the larger cylinders (i.e., 30B, 48X, 48Y) appears much less likely.

I. UF_6-FIRE PRODUCT REACTIONS

The reaction of UF_6 with H_2O, which occurs rapidly in the ambient environment, would also occur in a fire due to the large quantities of H_2O formed from the combustion of hydrocarbons. Free-radical reactions between UF_6 and combustion products would also be favored by the high temperatures of a fire. Possible reaction products include UF_4, HF, C, CF_x, and COF_2; fluorine will also substitute freely into hydrocarbon chains ($-C_nH_{2n}-$).(1) Under non-fire conditions, UF_6 and hydrocarbon oils have reacted explosively. Rapp(2) described consequent reaction products as "black carbonaceous smoke," "carbon and reduced uranium in the residue," "uranium in the reduced state and an elevated carbon content," "solid residues ... consisted of β UF_5 containing about 4% U_2F_9 in association with a small amount of fluorinated carbonaceous material," and "reduced uranium fluoride." Experimental results indicate that the "reaction between uranium hexafluoride and hydrocarbon oil becomes vigorous at 70 to 90°C, forming UF_4, carbon, and low molecular weight fluorinated compounds (CF_4, C_2F_6, C_3F_8, C_4F_{10})." He further states that "where excess UF_6 is involved the reduced uranium most probably would consist of some UF_5, U_2F_9 and/or U_4F_{17}." In the absence of kinetic data, the final chemical species resulting from a release of UF_6 into a fire and the corresponding energy increase cannot be determined. While a few well chosen experiments may provide useful information, obtaining sufficient data to predict with reasonable accuracy what occurs when UF_6 is released into a fire would require a major experimental program.(3)

Nevertheless, potential effects of the release of UF_6 into a fire can be evaluated. Several possible reactions involving UF_6 and CH_4, H_2, C, and CO--combustible materials chosen as surrogates for the broad range of gases present within a fire--are listed in Table 1 along with combustion reactions (leading to formation of H_2O and CO_2) and the UF_6 hydrolysis reaction. Consideration has been given to energy trade-offs occurring when the surrogate materials (e.g., CH_4, H_2, C, CO) react with UF_6 rather than O_2. Results of this comparison are given in Table 2; in all cases, more heat is released by reacting the surrogates with UF_6 rather than with O_2. On the other hand, the heat of reaction for UF_6 and H_2O is -101.5 kJ/mol UF_6, which exceeds the increased energy releases tabulated in Table 2. Consequently, energy release into the fire appears to be maximized by complete combustion of hydrocarbons along with the complete hydrolysis of UF_6.

If a carbon-to-hydrogen ratio approaching 2 (i.e., $-C_nH_{2n}-$) is assumed for a fuel contributing to a fire, a simple mass balance yields an off-gas composition of about 13% H_2O assuming dry air for combustion. This composition significantly exceeds ambient concentrations. When UF_6 is released into a fire environment--whether as a sudden, explosive release or in a slower release through a crack, the subsequent flashing and turbulence should yield rapid mixing and reaction of the UF_6, with either H_2O or combustible materials.

Table 1. Some Possible Reactions between UF_6 and Fire Products[a]

	Reactions	ΔH_{rxn}, kJ/mol	ΔG_{rxn}, kJ/mol
1.	$UF_6(v) + 2\ H_2O(v) \rightarrow UO_2F_2(s) + 4\ HF(v)$	-101.5	-123.8
2.	$UF_6(v) + 0.25\ CH_4(v) \rightarrow UF_4(s) + 0.25\ CF_4(v) + HF(v)$	-250.4	-239.9
3.	$UF_6(v) + H_2(v) \rightarrow UF_4(s) + 2\ HF(v)$	-309.4	-306.0
4.	$UF_6(v) + 0.5\ C(s) \rightarrow UF_4(s) + 0.5\ CF_4(v)$	-229.3	-199.1
5.	$UF_6(v) + CO(v) \rightarrow UF_4(s) + COF_2(v)$	-291.0	-241.6
6.	$CH_4(v) + 2\ O_2 \rightarrow CO_2(v) + 2\ H_2O(v)$	-802.3	-800.8
7.	$H_2(v) + 0.5\ O_2(v) \rightarrow H_2O(v)$	-241.8	-228.6
8.	$C(s) + O_2(v) \rightarrow CO_2(v)$	-393.5	-394.4
9.	$C(s) + 0.5\ O_2(v) \rightarrow CO(v)$	-110.5	-137.2

[a] The values of ΔH_{rxn} and ΔG_{rxn} are based on data taken from Ref. 4. Reference conditions are 25°C and 0.1 MPa.

Table 2. Energy Trade-offs for Reaction with UF_6 vs O_2

Reactant	Change in energy released (kJ/mol UF_6) (ΔH_{rxn} w/UF_6)	- (ΔH_{rxn} w/O_2)	= Net Change	Net increase in energy release to fire (%)
CH_4	-250.4	-802.3 / 4	-49.8	25
H_2	-309.0	-241.8	-67.2	28
C	-229.3	-393.5 / 2	-32.6	17
CO	-291.0	-393.5 - (-110.5)	-8.0	3

II. CYLINDER RUPTURE DUE TO FIRE

The time required to rupture a cylinder exposed to fire has been conservatively estimated. Results are compared to experiments conducted in 1965.

FIRE CONDITIONS

There are several sources of fire conditions which may be used for analysis of fire effects. NRC criteria are as follows:(5)

> Exposure of the whole specimen for not less than 30 minutes to a heat flux not less than that of a radiation environment of 800°C (1475°F) with an emissivity coefficient of at least 0.9. For purposes of calculation, the surface absorptivity must be either that value which the package may be expected to possess if exposed to a fire or 0.8, whichever is greater. ...

Buck and Belason included the following description of a design fire environment relative to a proposed ASTM standard:(6)

> A total heat flux of 174 kW/m^2 (15.28 $Btu/ft^2 s$) with components of 158 kW/m^2 (13.89 $Btu/ft^2 \cdot s$) radiative heat flux and 16 kW/m^2 (1.39 $Btu/ft^2 \cdot s$) convective heat flux, average flame temperatures of between 983°C (1700°F) and 1261°C (2300°F) ...

They also argue that "in ... large hydrocarbon pool fires, it [is] reasonable to assume an emissivity of 1.0" since "the flames only have to be 3 to 6 feet thick to be optically opaque."

The tabulated results presented subsequently assume a flame temperature of 1475°F and a flame emissivity of 1.0. It is also assumed (for the case of complete immersion in a fire) that the convective heat flux to the cylinder, which would be about 10% of the total heat flux based on the proposed ASTM standard, is negligible relative to other uncertainties.

CYLINDER RUPTURE CONDITIONS

Based on nominal cylinder characteristics (see Table 3), a cylinder containing the maximum quantity of UF_6 would be completely filled with liquid at 300°F. This condition was initially considered as a criterium for imminent rupture; however, more realistic failure conditions can be extrapolated from data obtained by hydraulically rupturing UF_6 cylinders. Such data are summarized in Table 4.

For cylinders--30B and smaller--that exhibit ductile failure (hoop stress), hydrostatic failure conditions obtained at room temperatures were extrapolated to fire conditions by multiplying the hydrostatic failure pressure and volume increase by a materials degradation factor of 0.35 based on an assumed temperature of 1200°F.(10) This factor was used for both steel and monel; however, a factor greater than 0.35 is more probable for monel (i.e., monel experiences less degradation than steel). Because data were not available for 5A and 8A cylinders, the following relation for determining failure pressure was used:

$$\sigma_u = P\, r/t \; . \qquad (1)$$

In this instance, σ_u was calculated from the failure pressure of a 12B cylinder, then failure pressures were evaluated for the smaller cylinders. The volume increase of 5A and 8A cylinders was assumed to be the same as that of a 12B cylinder.(11)

The failure mechanism for 10- and 14-ton cylinders is brittle fracture: the stiffening rings develop cracks where the ends are welded together that propagate inward through the tack weld joining the rings to the cylinders. If the stiffening rings were not present, the volume increase of these cylinders is expected to be comparable to that of the 30B cylinders. For these 10- and 14-ton cylinders, failure pressure at fire conditions was determined from Eq. 1 based on failure conditions for 30B cylinders; however, the volume increase was only slightly reduced from that determined from the hydrostatic rupture tests. The rationale for this approach is that brittle failure is not accelerated by higher temperatures, but there is a potential for a greater volume increase, up to about 10%, from hoop stress prior to failure. Assuming only a slight reduction in volume increase is therefore considered reasonable.(12)

Given estimates of the failure pressure and final volume of UF_6 cylinders, the final temperature of UF_6 can be estimated from physical property correlations for liquid density, compressibility, and vapor pressure. Estimated conditions for UF_6 cylinder failure in a fire are also presented in Table 4. The total heating requirements, from a range of initial conditions (solid UF_6 at 70°F through liquid UF_6 at 225°F), to the final rupture

Table 3. Cylinder Characteristics[a]

Type	Tare weight, lb	Maximum capacity, lb	Internal volume, ft^3	Internal diameter, in	Average length, in	Surface area, ft^2
5A	55	55	0.284	5	24.99	3.00
8A	120	255	1.319	8	45.34	8.61
12B	185	460	2.38	12	36.36	11.09
30B	1,400	5,020	26.0	29	68.02	52.21
48X	4,500	21,030	108.9	48	103.99	134.0
48Y	5,200	27,560	142.7	48	136.27	167.8

[a]Table values are based on Ref. 7.

Table 4. Estimated Conditions for Failure of UF_6 Cylinders Exposed to Fire

Cylinder Characteristics			Hydrostatic Testing Results[a]			Estimated Fire Failure Conditions		
Type	Material	Wall thickness, in.	Failure mode	Failure pressure, psia	Volume increase, %	Failure pressure, psia	Volume increase, %	Final UF_6 temperature, °F
5A	Monel	1/4				1900	20	434
8A	Monel	3/16				900	20	400
12B	Monel	1/4	Hoop stress	2265	53	800	20	396
30B	A516 steel	1/2	Hoop stress	2315	30	800	10	367
48X[b]	A285 steel	5/8	Brittle frac	1285	6.3	625	5	340
48Y	A516 steel	5/8	Brittle frac	1780	6.3	625	5	340

[a]See Refs. 8 and 9.

[b]Hydrostatic test results are from testing of a 48A cylinder.

conditions were estimated using UF_6 enthalpy correlations and a heat capacity for steel of 0.12 Btu/lb·°F.(13) It is conservatively assumed that the final cylinder wall temperature is equal to the final UF_6 temperature.

HEAT TRANSFER ANALYSIS

The starting point for evaluating the radiative heat flux from the fire to the cylinder is

$$Q = A_1 F_{12} \sigma (T_1^4 - T_2^4)/\left(\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1\right). \quad (2)$$

It is then assumed that the cylinder temperature is negligible relative to that of the fire. Noting that $A_1 F_{12}$ equals $A_2 F_{21}$ and assuming that the emissivity of the fire, ϵ_1, is 1, the following equation for the radiant heat flux to the surface of the cylinder is obtained:

$$q_2 = 0.173 \times 10^{-8} F_{21} \epsilon_2 T_1^4 . \quad (3)$$

For a cylinder totally immersed in a fire, $F_{21} = 1$; for a cylinder external to a fire, the view factor from the effective surface of the cylinder to the fire, F_{21}, can be approximated based on the surfaces illustrated on Fig. 1. While the view factor correlation utilized in the approximation is itself rigorous,(14) the effective geometry shown on Fig. 1 is only an approximation; the illustrated geometry is expected to become more reasonable as the separation distance between the fire and the cylinder increases. Reported values for the emissivity of the cylinder, ϵ_2, range from 0.3 or less for iron and steel to 0.95 for various paints and soot.(15)

The time to rupture for a cylinder exposed to fire is approximated by

$$\tau = 60\ E/q_2 A_2 . \quad (4)$$

Two cases are subsequently considered. The first assumes total immersion of the cylinder in the fire. The second assumes that the cylinder is outside the fire.

Case 1: A Cylinder Immersed in a Fire

It is assumed that the surface of a cylinder totally immersed in a fire rapidly blackens from soot; thus, it is reasonable to set the cylinder emissivity, ϵ_2, equal to 0.95. Also, $F_{21} = 1.0$ and A_2 is the total surface area of the cylinder. The radiative heat flux from the fire to the cylinder is calculated by Eq. 2, then the time to cylinder rupture is estimated from Eq. 3. Estimated time intervals to rupture are given on Fig. 2 for a range of initial conditions and a flame temperature of 1475°F; specific results assuming solid UF_6 initially at 70°F are tabulated in Table 5. A multiplication factor to obtain the time to rupture at other flame temperatures is given on Fig. 3. For example, a 48X cylinder that is estimated to rupture in 27.3 min at a flame

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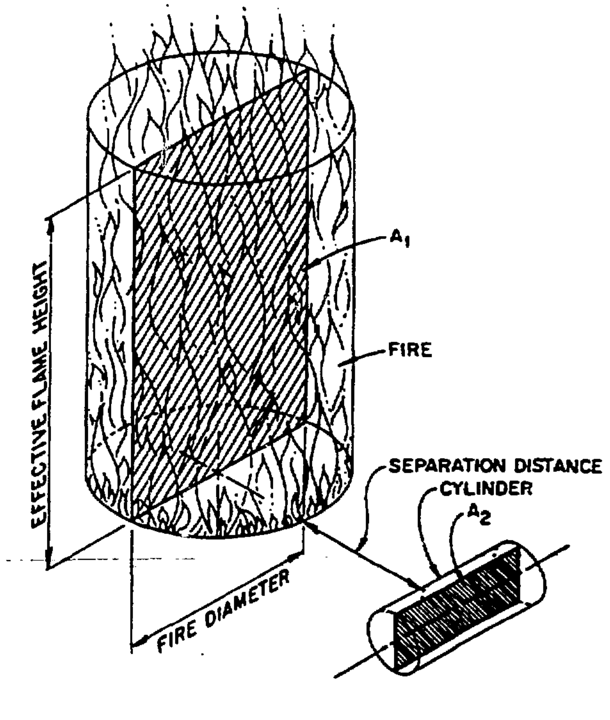

Fig. 1. Geometry for evaluating view factors between a fire and a cylinder.

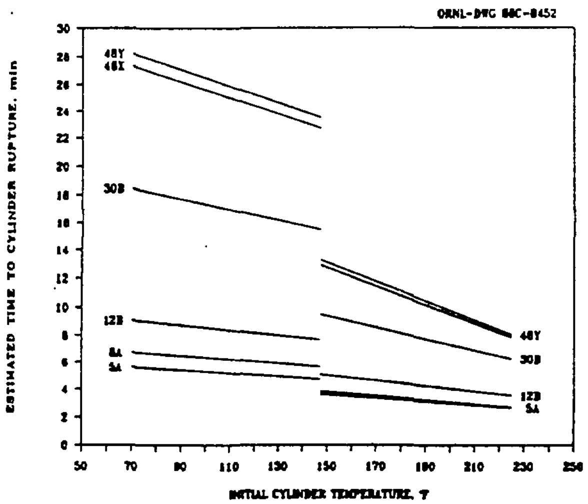

Fig 2. Estimated time interval to cylinder rupture based on a flame temperature of 1475°F.

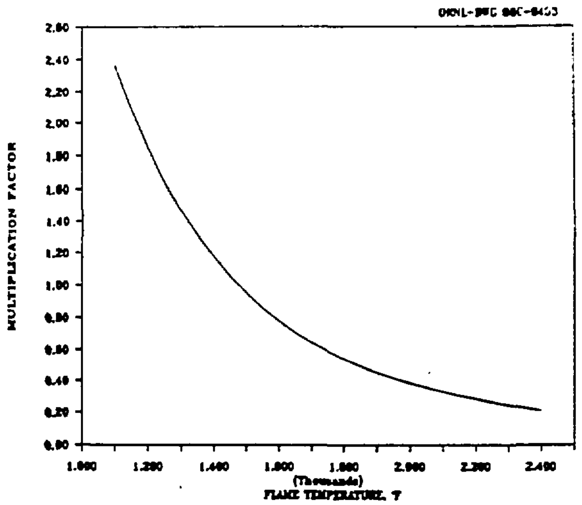

Fig. 3. Multiplication factor for adjusting the results given in Fig. 2 to temperatures other than 1475°F.

temperature of 1475°F would rupture at 12.3 min based on a 1900°F flame which yields a multiplication factor of 0.45.

Case 2: A Cylinder Adjacent to a Fire

For this second case, fires of several sizes were considered. Fire diameters at the ground surface of 10, 20, and 50 ft were selected, and effective flame heights twice the fire diameter were assumed based on the work of Mudan.(16) [Greater height to diameter ratios could have been assumed; but, since the fire is approximated as a right-circular cylinder (see Fig. 1) rather than as a cone, a ratio of 2 was considered a compromise.] Figure 4 summarizes view factors, F_{21}, from the cylinder to the fire; the view factors are not a strong function of cylinder size when separation distances exceed about 10 ft. A surface area multiplier, which is the ratio of the effective surface area (length x diameter) to the total surface area (see Table 4), is given in Table 6. For a cylinder

Table 5. Estimated Time Interval to Cylinder Rupture

UF_6 phase		Solid
Cylinder temperature		70°F
Flame temperature		1475°F
Heat flux		23,000 Btu/hr·ft_2
Cylinder type	**Total heat requirements, Btu**	**Time to rupture, min**
5A	6,400	5.7
8A	21,900	6.8
12B	38,000	9.1
30B	364,000	18.5
48X	1,400,000	27.3
48Y	1,810,000	28.2

adjacent to a fire, its emissivity, ϵ_2, can range from less than 0.3 up to 0.95, depending on the surface finish, as noted earlier.

To estimate the time to rupture for a cylinder adjacent to a fire multiply the time to rupture for a cylinder immersed in a fire (Fig. 2 or Table 5) by the flame temperature multiplication factor (Fig. 3) and the surface area multiplier (Table 6) and divide by the view factor (Fig. 4). If an emissivity other than 0.95 is assumed for the cylinder, multiply the result by 0.95 and divide by the assumed emissivity. For example, a 12B cylinder initially at 70°F will rupture in about 1 h when exposed to a 20-ft diam, 1900°F fire at a distance of 10 ft (i.e., 9.1 x 0.45 x 3.66 ÷ 0.24 = 62 min). Table 7 indicates time interval ranges needed to reach rupture conditions for a range of fire conditions.

RELATED STUDIES

In October 1965, cylinders containing from 5 to 250 lb of UF_6 were exposed to fire in a series of tests conducted at the Oak Ridge Gaseous Diffusion Plant (ORGDP).(17) These tests were conducted "to determine if the cylinders would hydrostatically or explosively rupture [and] the time available for fire fighting before either incident occurred." The cylinders were mounted where they would be completely within the fire. A summary of the tests is given in Table 8. During Test V, the cylinder wall temperature approached about 1000°F and UF_6 temperatures within the cylinder varied between 330 and 440°F at the instant the cylinder explosively ruptured. Mallett concluded that the tests "confirmed that [an] UF_6 cylinder rupture of explosive force is possible and that it can occur within a time sufficiently short as to possibly preclude fire fighting unless initiated very promptly. The explosions noted cannot be considered any more severe or hazardous than those due to other chemical or gas explosions. The amount of water blown from the tank by the force of

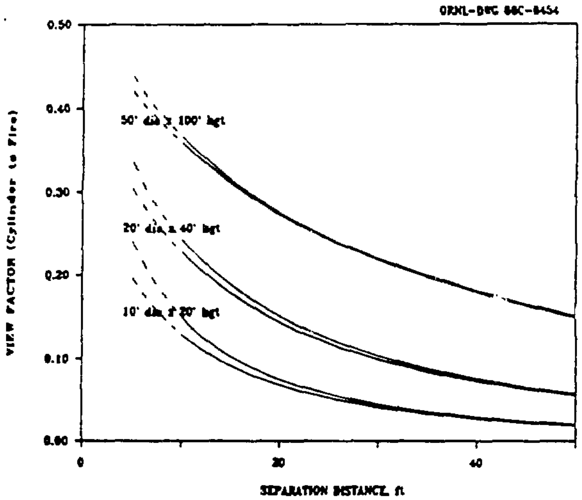

Fig. 4. View factors as a function of separation distance between fire and cylinder and fire size.

the explosion contributed largely to the fireball formation, a cause which, in most transportation accidents, is unlikely to be so available." Valve failures precluded explosions in Test I and IV.

Duret and Bonnard described the results of experimental and modeling efforts which included consideration of internal heat transfer in an UF_6 cylinder exposed to fire.(18) In a direct comparison with Mallett's results (which would be Tests III and V), they estimated a time to cylinder rupture of 8 min 40 s assuming a fire temperature of 800°C (1472°F); rupture would occur at an UF_6 temperature of 160°C (320°F). In their analysis, the cylinder wall temperature approached 600°C (1112°F) at the end of 6 min. Predicted failure durations for 30B and 48Y cylinders exposed to 800°C and 900°C fires were also presented (see Table 9).

UNCERTAINTIES IN THE ANALYSES

Direct comparison of time estimates to cylinder rupture based on the approach described herein (see Table 5) to the results of the ORGDP tests (see Table 8) shows a conservative estimate of that time. Estimated times were 5.7 and 6.8 min for 5A and 8A cylinders, respectively, assuming a fire temperature of 1475°F, while Mallett's data indicated actual rupture occurred at 8 min for a 5A-sized cylinder and at 8.5 and 10.5 min for two 8A-sized cylinders. A number of conservative assumptions were made in these analyses; a nonconservative assumption is offset by the conservative assumptions. The various assumptions and their impacts--both in general, as well as on the comparison between calculations and experiment--are discussed in the following paragraphs.

Cylinder wall temperature. It has been assumed for these analyses that the cylinder wall temperature will have a negligible impact on the heat flux. However, Mallett's data, as well as the modeling of Duret and Bonnard, indicate that wall temperatures

Table 6. Surface Area Multipliers for Case 2

Cylinder type	Multiplier
5A	3.46
8A	3.42
12B	3.66
30B	3.81
48X	3.87
48Y	3.69

Table 7. Range of Time Intervals to Rupture for a Cylinder Adjacent to a Fire, min[a]

Cylinder type	Separation distance (ft)		
	10	20	40
Fire temperature: 1900°F; Cylinder emissivity: 0.95			
5A	16 - 57	20 - 116	31 - *
8A	16 - 69	21 - *	32 - *
12B	23 - 98	30 - *	46 - *
30B	44 - *	58 - *	89 - *
48X	62 - *	83 - *	*
48Y	62 - *	82 - *	*
Fire temperature: 1475°F; Cylinder emissivity: 0.95			
5A	34 - *	45 - *	67 - *
8A	36 - *	47 - *	71 - *
12B	51 - *	67 - *	101 - *
30B	98 - *	*	*
48X	*	*	*
48Y	*	*	*
Fire temperature: 1900°F; Cylinder emissivity: 0.30			
5A	49 - *	64 - *	97 - *
8A	52 - *	67 - *	102 - *
12B	73 - *	95 - *	*
30B	*	*	*
48X	*	*	*
48Y	*	*	*
Fire temperature: 1475°F; Cylinder emissivity: 0.30			
5A	108 - *	*	*
8A	114 - *	*	*
12B	*	*	*
30B	*	*	*
48X	*	*	*
48Y	*	*	*

[a]The first number in each range corresponds to an initial condition of liquid UF_6 at the triple point (147.3°F) exposed to a 50-ft diameter fire; the second number corresponds to solid UF_6 at 70°F and a 10 ft fire. An asterisk, *, indicates a time greater than 2 h.

Table 8. Summary of ORGDP Fire Tests

Test	I	II	III	IV	V
Cylinder Data					
Diameter, in.	3.5	5	8	5	8
Length, in.	7.5	30	48	30	48
Material	Monel	Monel	Nickel	Monel	Nickel
UF_6 mass, lb	5	55	248.9	53.04	245
Failure Data					
Mode	Valve failure	Explosion	Explosion	Valve failure	Explosion
Time, min	a	10	10.5	b	8.5

a. Two cylinders were tested simultaneously with valve failures occurring at 4 min and 6 min. The first failure occurred when teflon seals melted; the second when silver solder melted.

b. The two cylinder valves failed at 8 min and 9 min. The release was complete in 10 min.

exceeding 1000°F can occur. The reduction in heat flux resulting from the various wall temperatures is shown in Table 10. A further increase in the time to cylinder rupture would result from the heat capacity of the steel due to the additional temperature rise. Further analysis taking into account the complex phenomena of heat transfer within the cylinder is required to estimate cylinder wall temperatures.

UF_6 Enthalpy. The enthalpy of the compressed UF_6 at the point of rupture has been estimated from a correlation for saturated liquid enthalpy at lesser temperatures. This correlation is expected to underestimate the saturated enthalpy at higher temperatures. Accounting for the effects of compression, and improving the enthalpy correlation for higher temperatures, would increase the final enthalpy and, hence, the time to rupture.

Emissivity. In the analysis of a cylinder immersed in a fire, an emissivity of 1 was used for the fire. This assumption appears reasonable for large fires. However, relative to the argument of Buck and Belason, a fire emissivity less than 1 might be appropriate, based on the relative size of the fire and cylinders, for estimating the time relative to Mallett's data. Cylinder emissivity could be less than 0.95 which was chosen as an upper limit likely to be obtained in a fire environment. Lesser emissivities would increase the estimated time to rupture.

Convective heat transfer. Convective heat transfer accounts for about 10% of the total heat flux in a fire environment. Inclusion of the convective component would decrease the time required to heat a cylindar to the point of rupture. Neglect of the convective flux is offset by the other assumptions already discussed.

Cylinder radiation and convection to environment. The cooling effects of radiation and convection from the cylinder to the environment for cylinders adjacent to a fire were not considered. Inclusion of such effects would increase the predicted time to rupture for cylinders not totally immersed in a fire.

CONCLUSIONS

The estimated time intervals to rupture for UF_6-filled cylinders exposed to fire should be considered preliminary, conservative estimates. Resolution of the various uncertainties discussed above should increase the estimated time intervals. The data of Mallet indicate that increased estimates are plausible. Consideration of cylinder expansion prior to rupture significantly impacts the time to rupture.

The estimated time intervals given on Fig. 2 and in Table 5 indicate that all sizes of cylinders may rupture within 30 min when totally immersed in a fire, although resolution of the uncertainties may

Table 9. Time to Failure for Cylinders Exposed to Fire (Estimates by Duret and Bonnard)

Cylinder type	Fire temperature, °C	Time to failure, min
30B	800	35
30B	900	28
48Y	800	61
48Y	900	47

Table 10. Reduction in Radiant Heat Flux, %, Due to Cylinder Wall Temperature

Wall temperature, °F	Flame temperature 1475°F	Flame temperature 1900°F
300	2.4	1.1
600	9.0	4.1
1000	32.	15.

increase time estimates for the 48X and 48Y cylinders beyond 30 min. For cylinders adjacent to fires, rupture of large cylinders appears much less likely. Test results show that valve failure may occasionally preclude cylinder rupture.

When a cylinder fails in a fire, the release of UF_6 into the fire will add energy to the fire.

REFERENCES

1. Barber, E. J., Oak Ridge Gaseous Diffusion Plant, Oak Ridge, Tennessee, personal communication, December 18, 1985.

2. Rapp, Karl E., "The Pattern of Explosive Reaction Between Uranium Hexafluoride and Hydrocarbon Oils," K/GD-1631, Rev. 1, Oak Ridge Gaseous Diffusion Plant, Oak Ridge, Tennessee, March 21, 1986.

3. Barber, E. J., personal communication, January 23, 1987.

4. J. Phys. Chem. Ref. Data., Vol. 11, Supple. 2, 1982.

5. 10 CFR Part 71.73(c)(3), August 24, 1983.

6. Buck, Michael E., and Belason, E. Bruce, "ASTM Test for Effects of Large Hydrocarbon Pool Fires on Structural Members," Plant/Operations Progress, Vol. 4, No. 4, pp. 225-229, October 1985.

7. "Uranium Hexafluoride: Handling Procedures and Container Criteria," ORO-651, Rev. 4, Oak Ridge Operations Office, U.S. Energy Research and Development Administration, Oak Ridge, Tennessee, p. 73, April 1977.

8. Barlow, C. R., Oak Ridge Gaseous Diffusion Plant, Oak Ridge, Tennessee, personal communication, March 29, 1988.

9. Barlow, C. R., Ziehlke, K. T., and Pryor, W. A., "Effects of Fire Exposure on Integrity of UF_6 Shipping Cylinders," K-2056, Martin Marietta Energy Systems, Inc., Oak Ridge, Tennessee, June 17, 1985.

10. "Military Standardization Handbook: Metallic Materials and Elements for Aerospace Vehicle Structures," MIL-HDBK-5C, Department of Defense, Washington, D.C., p. 2-18, September 15, 1976.

11. Hammond, C. R., Martin Marietta Energy Systems, Inc., Oak Ridge, Tennessee, personal communication, March 29, 1988.

12. Theiss, T. J., Martin Marietta Energy Systems, Inc., personal communication, March 30, 1988.

13. Perry, Robert H., and Chilton, Cecil H., Chemical Engineers' Handbook, 5th edition, McGraw-Hill Book Company, New York, p. 3-136, 1973.

14. Hsu, Chai-Jung, "Shape Factor Equations for Radiant Heat Transfer between Two Arbitrary Sizes of Rectangular Planes," The Canadian Journal of Chemical Engineering, Vol. 45, pp. 58-60, February 1967.

15. Siegel, Robert, and Howell, John R., Thermal Radiation Heat Transfer, 2nd ed., Hemisphere Publishing Corporation, Washington, D.C., pp. 832-5, 1981.

16. Mudan, Krishna S., "Hydrocarbon Pool and Vapor Fire Data Analysis," DOE/EP/16008-1, A. D. Little, Inc., Cambridge, Massachusetts, p. 100, October 1984.

17. Mallett, A. J., "ORGDP Container Test and Development Program: Fire Tests of UF_6-Filled Cylinders," K-D-1894, Oak Ridge Gaseous Diffusion Plant, Oak Ridge, Tennessee, January 12, 1966.

18. Duret, B. and Bonnard, J. C., "Behavior of UF_6 Package in Fire--Comparison of Calculations with Fire Experiment," PATRAM '83 Proceedings, Seventh International Symposium on Packaging and Transportation of Radioactive Materials, New Orleans, Louisiana, May 15-20, 1983, CONF-830528-Vol. 1, Oak Ridge National Laboratory, Oak Ridge, Tennessee, pp. 747-754, December 1983.