Lockheed Martin Energy Systems Engineering
Engineering Analysis

UF_6 CYLINDER ACCIDENT SIMULATIONS (1475°F REGULATORY FIRE)

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Review and Approval

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INTRODUCTION

This "Design Analysis Calculation" (DAC) has been prepared in support of the following projects:

1. Preparation of the K-25 Site Cylinder Storage Yard Final Safety Analysis Report (SAR).

2. Upgrade of the Gaseous Diffusion Plant Safety Analysis Reports (GDP SARs) for the Portsmouth and Paducah GDPs.

3. Preparation of the Depleted UF_6 Programmatic Environmental Impact Statement (PEIS).

The primary purpose of this DAC is to document the simulation of UF_6 cylinders engulfed in a 1475°F, 30-min fire to determine (a) for an unbreached cylinder, the time to rupture, the amount of UF_6 released "instantaneously" at the time of rupture, and the time dependent release of UF_6 after the rupture and (b) for an initially breached cylinder, the time dependent release of UF_6. These simulations of 14-ton thin- and thick-walled cylinders were made using 6FIRE and SUBLIME which have been documented by Williams *[WRW96a]* and Anderson *[JCA96]*. This DAC also addresses the time to failure of smaller UF_6 cylinders and documents the maximum heel quantities of UF_6 that can be contained by 2½-, 10-, and 14-ton cylinders engulfed in fire without rupturing.

MODELING ASSUMPTIONS

The simulations undertaken in this DAC are predicated on two accident "scenarios" which may be outlined as follows:

(a) an accident results in a fuel spill ... the fuel flows under a cylinder and ignites ... if the fire is of sufficient duration, the cylinder ruptures releasing UF_6 already in the liquid or vapor state ... the fire may continue for a period of time after the rupture ... during the remainder of the fire and subsequent to the fire as the cylinder cools, additional UF_6 sublimates

(b) an accident results in a cylinder being breached and in a fuel spill ... the fuel flows under the breached cylinder and ignites ... during the fire and subsequent to the fire as the cylinder cools, UF_6 sublimates

The outlined "scenarios" may be appropriate as stated or may be subparts of larger scenarios. For example, multiple cylinders may be involved, or perhaps both breached and unbreached cylinders are involved as the result of an aircraft accident. If multiple cylinders are involved, then appropriate application of the source terms presented in this DAC must be made by the users thereof.

This DAC presents 6FIRE and SUBLIME results for the two scenarios outlined above for 48G (thin-walled) and 48Y (thick-walled) 14-ton cylinders. The time to failure of other types of UF_6 cylinders is addressed on the basis of results presented herein and other documented results.

Cylinder characteristics used in the analyses described herein are presented in Table 1 and are derived from ORO-651, Rev.4 *[ORO/4]* except for materials of construction and the characteristics for the 48T cylinder. Characteristics for the thin-walled 48T cylinder were assumed equal to those of a thick-walled 48X cylinder except for wall thickness. Information in Rev. 5 and 6 of ORO-651 *[ORO/5; ORO/6]* indicates specific steels used for constructing some of the cylinders. Information on cylinder procurement history and materials of construction also appear in a paper by Ziehlke and Barlow *[KTZ]*. This information demonstrates specifically for some cylinders—and the inference is drawn for other cylinders—a change in the material of construction used from A-285 to A-516 steel in the late 1970s. 30B and 48Y cylinders, which were procured after 1978 *[KTZ]*, are assumed to be constructed of A-516 steel; all other cylinders listed above are considered to be constructed of A-285. A-285 has a lower heat capacity and a lower ultimate stress than A-516, so assuming cylinders are constructed of A-285 steel should result in conservative (i.e., lower) estimates of the time to failure. Principal differences among the 48-in. cylinders are material of construction, wall thickness, and overall size (i.e., length, which impacts cylinder weight and UF_6 capacity).

Other assumptions utilized in 6FIRE and/or SUBLIME simulations include:

- Cylinders are assumed to contain 28,000 lb of UF_6
- Cylinders are fully engulfed in a regulatory fire †
- Fire duration = 30 min †
- Fire temperature = 1475°F †
- Ambient temperature = 100°F
- Initial temperature of cylinder and UF_6 equals ambient temperature
- Emissivity of fire = 0.9 † in 6FIRE, 1.0 in SUBLIME
- Emissivity of cylinder = 0.8 † (in both programs)
- Failure mode: hoop stress exceeds ultimate stress (see Williams *[WRW96a]* for ultimate stress data)
- Cylinders remain essentially intact after ruputure; UF_6 solids remain inside cylinders

Assumptions marked with a dagger (†) are predicated on regulatory fire conditions governing package certification which assume a package is fully engulfed in a fire that is a part of a prescribed sequence of events *[10CFR71]*; actual fire temperatures may range from somewhat less than 1475°F to several hundred degrees higher, but actual fire-package geometry may not reflect a fully engulfed assumption.

For the evaluation of maximum heels, the ultimate stress algorithms appearing in the STRESS subroutine of 6FIRE *[WRW96a]* are applied to determine the failure pressure of the cylinders. (Use of these algorithms has been validated by the work of Luk and Webb *[KHL96a and KHL96b]*.) These evaluations are predicated on a regulatory fire temperature of 1475°F leading to an assumed cylinder wall temperature of 1475°F. The UF_6 vapor density corresponding to the failure pressure and a temperature of 1475°F is

Table 1. Cylinder Characteristics

Nominal cylinder type	2½-ton		10-ton		14-ton	
Model	30A	30B	48T	48X	48G	48Y
Wall characterization	—	—	thin-walled	thick-walled	thin-walled	thick-walled
Material of construction	A-285	A-516	A-285	A-285	A-285	A-516
Inner diameter, in.	29.1875	29	48	48	48	48
Cylinder thickness, in.	0.406	0.5	0.3125	0.625	0.3125	0.625
Cylinder length, in.					132.74	136.27
Cylinder weight, lb					2600	5200
Cylinder shell surface area, ft^2					164.1	167.8
UF_6 surface area, ft^2					126.3	129.3
Minimum cylinder volume, ft^3	25.65	26.0	108.9	108.9	139.0	142.7

multiplied by the minimum volume of each cylinder to determine the maximum amount of UF_6 the cylinder can contain without failure. No valve leakage is assumed.

RESULTS

Results of the 6FIRE and SUBLIME simulations for the 14-ton cylinders identified in the preceding section are summarized in Table 2 and Fig. 1. Predicted failure times for initially unbreached cylinders are 12.2 and 23.9 min for 48G and 48Y cylinders, respectively. Table 3 tabulates some of the data plotted in Fig. 1 and also provides additional information to support atmospheric dispersion analyses. That information includes the temperature and the vapor mass fraction of the UF_6 being released at the time of initial rupture as well as the temperature of the vapor subsequently sublimed. The initial release of UF_6 includes all vapor and liquid in the cylinder at the time of rupture; the liquid is assumed to flash and mix with the vapor forming a solid-vapor mixture at the sublimation temperature of UF_6 (solids formed upon flashing would be entrained in the plume). The equation used for calculating the vapor fraction is the following:

$$X = \{ [(m_{SHL}H_{SHL} + m_{SHV}H_{SHV}) / (m_{SHL} + m_{SHV})] - H_{S@T_s} \} / [H_{V@T_s} - H_{S@T_s}]$$

where
- X = vapor mass fraction
- m = mass
- H = enthalpy
- SHL = superheated liquid
- SHV = superheated vapor
- $S@T_s$ = solid at sublimation temperature
- $V@T_s$ = vapor at sublimation temperature

Table 2. Summary of 6FIRE and SUBLIME Results

	a. Thermal rupture		b. Initial breach	
	48G	48Y	48G	48Y
6FIRE Results				
Initial UF_6 mass, lb	28000	28000	28000	28000
Time of rupture, min	12.2	23.9	0†	0†
Composition at rupture, lb (%) Solid	24163 (86.3)	21984 (78.5)		
Liquid	3523 (12.6)	4744 (16.9)		
Vapor	314 (1.1)	1272 (4.6)		
Cylinder pressure at rupture, psia	231.8	670.9		
Liquid temperature at rupture, °F	260.0	284.9		
Vapor temperature at rupture, °F	672.7	611.5		
Average shell temperature at rupture, °F	1125	1085		
Initial release, lb	3837	6016	0†	0†
SUBLIME Results				
Time from rupture to end of fire, min	17.8	6.1	30	30
Vapor sublimated during remainder of fire, lb	2975	924	4240	3213
Vapor temperature at end of fire, °F	912	882	912	905
Vapor sublimated after fire, lb	1192	2670	1192	2733
Duration of post-fire release, min	91.4	205.7	91.4	206.1
Total UF_6 released, lb (% initial UF_6)	8004 (28.6)	9610 (34.3)	5432 (19.4)	5946 (21.2)

† A cylinder will always contain some UF_6 vapor, some of which may be released when a cylinder is breached. This quantity of material, practically speaking, would be insignificant relative to uncertainties in the overall modeling of a cylinder that is breached coincident with the initiation of a fire.

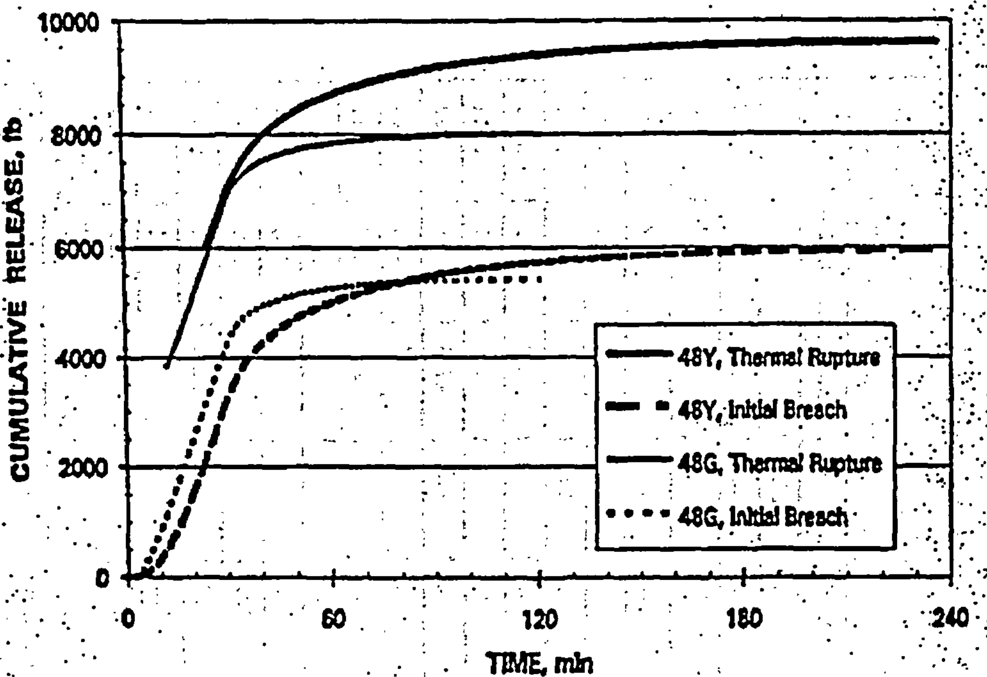

Fig. 1. Cumulative mass of UF_6 released from 14-ton 48G (thin-walled) and 48Y (thick-walled) cylinders exposed to a 1475°F, 30-min fire.

Figure 2 plots the density of UF_6 vapor as a function of pressure for a constant temperature of 1475°F *[JCA]*. At these temperatures and pressures, the density is essentially equal to the density obtained assuming ideal gas behavior; ideal densities were used for estimating the maximum heel. Estimates of maximum heel quantities that can be contained in 2½-, 10-, and 14-ton cylinders engulfed in a 1475°F regulatory fire are provided in Table 4. Maximum quantities of UF_6 range from 60.0 lb (30A cylinder) to 408.4 lb (48Y cylinder).

DISCUSSION OF RESULTS

The results presented in this DAC are predicated on an assumed regulatory fire temperature of 1475°F. It should be noted that fire temperatures in excess of 2000°F have been documented *[JHC96]*. Higher temperatures will result in shorter times to failure; however, algorithms yet to be completed in 6FIRE may extend times to failure *[WRW96a]*. Results presented by Williams *[WRW96a]* demonstrate that time to failure is a strong function of fire temperature: increasing the fire temperature to 2000°F would cut the time to failure by about a factor of four. The uncertainties introduced by fire temperature (an input) predominate over all other uncertainties, either in modeling or resulting from input (see *[WRW96a]* for additional discussion of modeling uncertainties). Williams also presents results demonstrating that some partially filled cylinders may survive longer than nominally filled cylinders (the 28,000-lb loading assumed in this DAC exceeds the typical nominal fill limit of 95% filled at 250°F). Note that the uncertainties in

Table 3. Additional Information Provided to Support Atmospheric Dispersion Analyses

a. Thermal rupture

	48G		48Y	
	T, °F	m_{cum}, lb	T, °F	m_{cum}, lb
"Initial" conditions	t = 12.2		t = 23.9	
	X = 0.757		X = 0.923	
	133.8	3837	133.8	6016
t, min	*Transient conditions, X = 1*			
15	893	4267		
20	910	5105		
25	911	5957	837	6170
30	912	6812	882	6940
35	562	7292	685	7543
40	429	7505	575	7917
50	302	7727	447	8386
60	239	7843	372	8683
75	188	7935	301	8975
90	160	7979	255	9167
105	144	7999	224	9301
120	134	8004	201	9396
150			170	9516
180			152	9578
"Final" conditions	t = 121.4		t = 235.7	
	133.8	8004	133.8	9610

b. Initial breach

	48G		48Y	
	T, °F	m_{cum}, lb	T, °F	m_{cum}, lb
t, min	*Transient conditions, X = 1*			
0	133.8	0	133.8	0
5	691	191	407	62
10	882	851	644	330
15	909	1680	792	850
20	911	2531	863	1558
25	912	3385	893	2365
30	912	4239	905	3213
35	562	4720	696	3844
40	429	4933	581	4229
50	302	5155	451	4708
60	239	5270	374	5010
75	188	5363	302	5305
90	160	5407	256	5499
105	144	5426	225	5633
120	134	5432	201	5730
150			171	5851
180			152	5913
"Final" conditions	t = 121.4		t = 236.1	
	133.8	5432	133.8	5946

T = temperature, °F m_{cum} = cumulative mass of UF_6 released, lb t = time, min X = vapor mass fraction

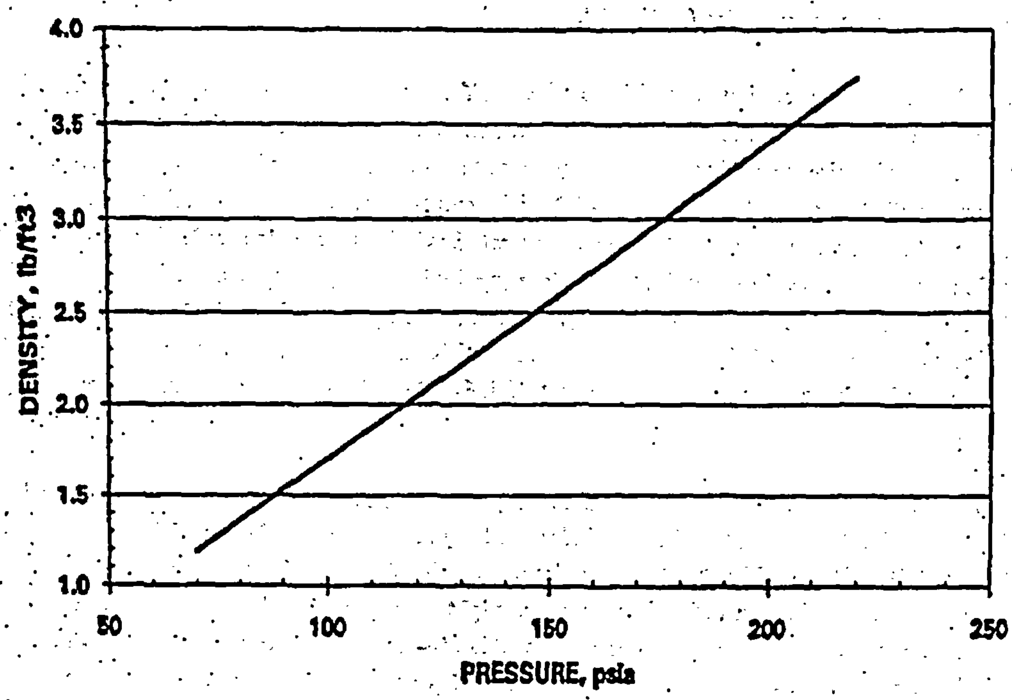

Fig. 2. Density of UF_6 vapor vs. pressure at 1475°F.

Table 4. Maximum UF_6 Heel Quantities Predicated on a 1700°F Fire

Cylinder Type	Material of Construction	Failure Pressure at 1475°F, psia	Vapor Density, lb/ft³	Minimum Cylinder Volume,† ft³	Maximum Heel, lb
2½-ton (30A)	A-285	138.0	2.34	25.65	60.0
2½-ton (30B)	A-516	217.9	3.69	26.0	96.0
Thin-walled 14-ton (48G)	A-285	72.9	1.24	139.0	171.7
Thin-walled 10-ton (48T)	A-285	72.9	1.24	108.9	134.5
Thick-walled 10-ton (48X)	A-285	130.3	2.21	108.9	240.5
Thick-walled 14-ton (48Y)	A-516	168.8	2.86	142.7	408.4

† Minimum cylinder volumes based on Table 9 of *Uranium Hexafluoride: Handling Procedures and Container Descriptions*, ORO-651, Rev. 5 (DE87014088), September 1987, except for 48T cylinders which are assumed to have a minimum volume equal to a 48X cylinder.

fire temperature also impact the estimation of maximum heel quantities; higher temperatures decrease the estimates of maximum quantities *[WRW96c]*.

Reported results corresponding to the failure of the 48Y cylinder are based on the last successful iteration of the 6FIRE program in the simulation undertaken pursuant to this current analysis. Fig. 3 demonstrates that failure was imminent based on the convergence of the hoop stress and ultimate stress curves. The final iteration for 6FIRE occurred at 1434 sec (23.9 min); extrapolation of information from this run indicates failure would occur at 1454 sec (24.2 min). Several simulations were also made that differed from the specific case of interest only in the fire temperature supplied as input; extrapolation of these successful runs projects a failure time of 1442 sec (24.0 min). Successful completion of the 6FIRE simulation at 1475°F would result in more UF_6 being released at the time of failure; however, this increase would be, for the most part, offset by a decrease in the amount of UF_6 released by sublimation subsequent to cylinder rupture.

At the elevated temperatures and pressures occurring within a cylinder engulfed in fire, cylinder valves may leak or fail prior to the rupture of the cylinder resulting in the release of some UF_6; such failures were noted by Mallett *[AJM]*. Elliott *[PGE]* provides information that valve leak rates of a few standard cubic feet per minute of nitrogen ($SCFM_{N2}$) or more might be expected under fire conditions (which *may* translate to about a pound per minute of UF_6 per $SCFM_{N2}$ based on a very cursory evaluation). Figure 2 of Elliott's paper indicates leakage exceeds 1 $SCFM_{N2}$ as the pressure approaches 100 psig (given a constant temperature of about 1450°F); Table 2 indicates leakage exceeds 0.5 $SCFM_{N2}$ as the valve temperature exceeds the range of 800 to 1000°F (given a constant pressure of about 250 psig). Leakage should not be expected to preclude failure; also, the amount of material released prior to rupture is not expected to be significant relative to the overall release of material before, during, and after the failure of a cylinder.

It was assumed that the fire lasted 30 min; the fire then stopped and the cylinder cooled by convection and radiation to the environment. If the fire lasts longer than 30 min, then more UF_6 would be sublimated. On the other hand, if the fire is extinguished at an earlier time (as opposed to the tacit assumption of simply burning out at 30 min), then the process of extinguishing the fire may also quench the cylinder which would decrease the amount of UF_6 sublimated; however, the formation and release of HF by water introduced into a breached cylinder would then need to be evaluated.

The emissivity of the fire has been assumed to be 0.9 in 6FIRE. This is a reasonable value, which has been adopted for evaluating the effects of fire on packaging *[10CFR71]*, and it is consistent with a fire that has been tacitly assumed to have a surface approximating the footprint of the cylinder. It is noted that fire emissivity approaches 1 as the flame thickness extends from 3 to 6 ft or more *[Buck]*. The emissivity of the fire (or environment) is 1 in SUBLIME; this value is conservative during the fire and appropriate for the postfire analysis when the cylinder radiates to the environment. An emissivity of 0.8 appears to be a reasonable estimate of cylinder emissivity. Higher emissivities would increase the rate of heat transfer and decrease the time to rupture.

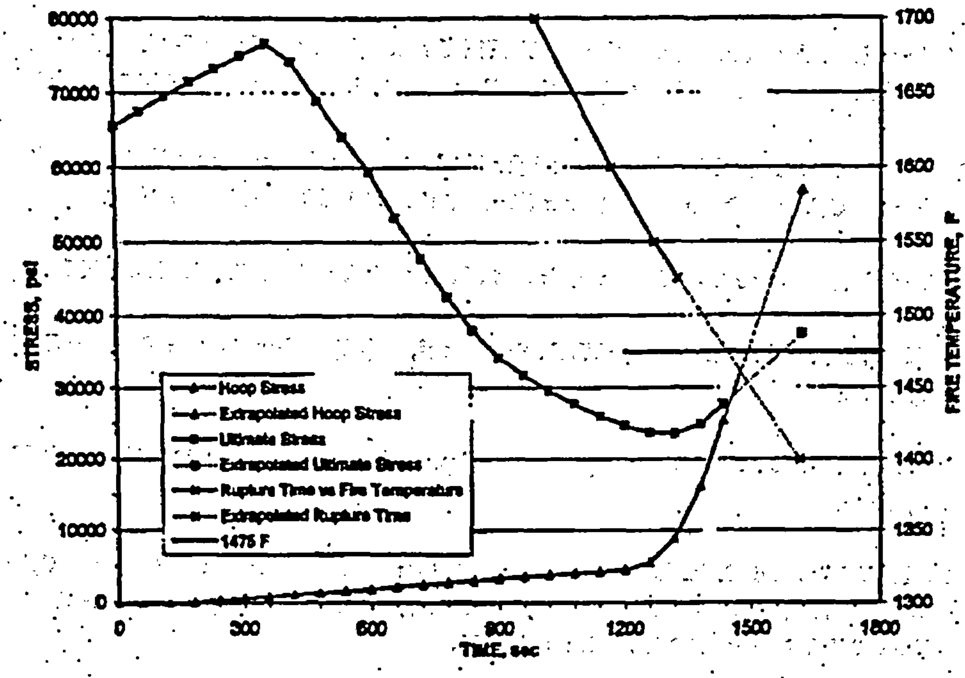

Fig. 3. Stress results for the 48Y 6FIRE simulation at 1475°F extrapolated to failure. Failure times from completed 6FIRE runs at higher temperatures are also extrapolated to failure.

The current evaluations consider cylinders fully engulfed in a regulatory fire. If a cylinder is not fully engulfed (e.g., the cylinder extends only partially into a pool or it is partially shielded from direct radiation by other cylinders) then the time to failure should increase. However, consideration of non-regulatory cylinder-fire geometries would also necessitate the use of actual fire temperatures.

This study has only considered "like-new" cylinders. Degradation due to corrosion or other damage may reduce estimated times to failure.

This study has determined best estimates of times to failure for 14-ton cylinders. Based on this and other studies and experiments *[WRW96a; WRW96b]*, the time to failure of thin-walled 10- and 14-ton cylinders exposed to a regulatory fire is less than 15 min; thick-walled 10- and 14-ton cylinders as well as 2½-ton cylinders will fail between 15 and 30 min.

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