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Source Term Evaluation During Seismic Events in the Paducah Gaseous Diffusion Plant

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**SOURCE TERM EVALUATION
DURING SEISMIC EVENTS
IN THE PADUCAH GASEOUS DIFFUSION PLANT**

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Source Term Evaluation During Seismic Events in the Paducah Gaseous Diffusion Plant

1. INTRODUCTION

The '00' buildings are expected to collapse (per guidance from structure evaluation) during a seismic event in which acceleration level exceeds 0.15g. All roof beams may slip off supports, and collapse. Equipment may slip off from supports and fall onto the floor. The cell floor is also supposed to collapse due to structural instability and distortion due to excessive acceleration forces. Following structure collapse, expansion joints in the process piping and joints between the piping and equipment are expected to fail. Preliminary analysis showed that converters are very likely to remain intact. The UF_6 gas released from the break will rapidly interact with moisture in the air to produce UO_2F_2 and HF with exothermic energy released of ~ 0.32 MJ/kg of UF_6 reacted. Depending on the degree of mixing between UF_6 gas, its reaction products, air and freon (R-114), there may occur a strong buoyancy force to disperse UO_2F_2 aerosol particles that are subjected to the gravitational force for settling. Such a chemical reaction will also occur inside the converters. A substantial amount of UF_6 must be stagnated at the bottom of the converters. At the interface between this stagnated UF_6 and air, UF_6 gas will diffuse into the air, undergo the chemical reaction with moisture there, and eventually be released through the break. Furthermore, lubricant oil fire in the building, if it occurs, will enhance the UF_6 release into the atmosphere. The purpose of this study is to evaluate source term (UO_2F_2 and HF) during such a seismic event. This study takes an approach using multiple steps as follows:

- (1) Source term evaluation at the break due to mixing between UF_6 and air along with thermal buoyancy induced by chemical reaction energy,
- (2) Evaluation of additional source term from the converters in which a substantial UF_6 vapor remains, and
- (3) Source term evaluation with lubricant oil fire

2. DATA

The amount of UF_6 initial release into the air at the break is based on a few simple values: the total UF_6 inventory in the '00' buildings minus the amount of UF_6 that can be stagnant in the bottom of the on-stream '00' converters. From other work we believe that the

converters and process piping will remain largely intact (no crushing) after the building collapse, but the expansion joints and other piping/equipment connections will fail. The motors and compressors are also expected to stop very rapidly once the building begins to collapse. Since UF_6 gas is much denser than air, it will tend to flow to the lowest point in the system. In most of the piping and related equipment, we cannot reasonably expect the UF_6 gas to remain inside the process equipment, as breaks may occur at or very near the lowest points. However, the converters have a significant volume below the level of the UF_6 inlet and outlets. UF_6 gas is therefore expected to be stagnant in the bottom of the converters.

The total inventory in the '00' process buildings is easily calculated from the building power level. The volume available for pooling is the number of on-stream converters times the pool volume in each converter. The total volume available for stagnation times the density of UF_6 gas at process temperatures and atmospheric pressure gives the amount of inventory stagnated in the bottom of the converters. The remaining inventory is assumed to be released into the building immediately when the building collapsed. The UF_6 in the converters will react much more slowly, and any release will be limited by the barrier in the converter shell.

Basic '00' Process Building Information

- '00' process building volume, after collapse = $640 \text{ ft} \times 804 \text{ ft} \times \sim 10 \text{ ft}$ ($195.1 \text{ m} \times 804 \text{ m} \times \sim 3 \text{ m}$) = $5 \times 10^6 \text{ ft}^3$ ($1.42 \times 10^5 \text{ m}^3$)
(the volume occupied by the process is not excluded because the process is open to the atmosphere)
- Each '00' process building cross section area = $640 \text{ ft} \times 804 \text{ ft}$ ($195.1 \text{ m} \times 804 \text{ m}$) = $514,560 \text{ ft}^2$ ($47,804 \text{ m}^2$)
- Average process gas temperature = 260°F (400 K) (from Steve Chambers gradient for 2200 MW)
- Conversion factor for MW to Inventory = 407.8 lb (185 kg) UF_6/MW for '00' equipment
- Total Cell Volume = $11,162 \text{ ft}^3$ (316.1 m^3)
Combined Volume of the 10 converters = $8,060 \text{ ft}^3$ (228.2 m^3)
Volume of piping, compressors, & etc = $3,102 \text{ ft}^3$ (87.8 m^3)

- Combined pool volume of the 10 converters = 1,818 ft³ (51.5 m³)
Density of UF₆ gas at 260 °F (400 K) and 1 atm = 0.6 lb/ft³ (9.6 kg/m³)
Specific heat capacity of UF₆ gas at 260 °F (400 K) and 1 atm = 0.089 BTU/lb-°F
(0.3726 kJ/kg-C)

2200 MW Case

- Total '00' building inventory = 123,500 lb. (56,019 kg) of UF₆ per 80 cells
- Pooled Inventory remaining in converters = 59,589 lb. (27,029 kg) of UF₆ (48%) per 80 cells
- Inventory released immediately to building = 63,911 lb. (28,990 kg) of UF₆ (52%) per 80 cells

1600 MW Case

- Total '00' building inventory = 100,870 lb. (45,754 kg) of UF₆ per 80 cells
- Pooled Inventory remaining in converters = 59,589 lb. (27,029 kg) of UF₆ (59%) per 80 cells
- Inventory released immediately to building = 41,281 lb. (18,725 kg) of UF₆ (41%) per 80 cells

Note that the pooled inventory remained the same in both cases; that is because the number of '00' cells on-stream did not change, and therefore the volume available for pooling remained unchanged.

Releases from Tie-Lines to '000' Buildings

The collapse of the two '00' process buildings at Paducah would of course break the tie lines connecting them to the other process buildings. The total contents of the tie lines is about 2000 lb. (907 kg) of UF₆. Because the tie lines and the process equipment they connect to are operating well below atmospheric pressure, little else would be released. At 2200 MW, the pressures in the tie lines are about 12 psia (82.7 kPa) for the B stream and 2.5 psia (17.2 kPa) for the A stream. When these pipes are opened to the atmosphere, air will rush in both the A- and B-lines, bringing the pressure up to 1 atmosphere. If the other process buildings continue to operate after the earthquake, the compressor at the outlet of the tie line will lose it's effectiveness because of the inrushing air. Axial compressors in the GDPs typically operate with a pressure ratio of about 5 when pumping pure UF₆. Test loop

experiments have shown that the same compressors can only support a pressure ratio of 1.2 when operated on light gasses such as air or HF. In addition, sudden changes in gas composition and/or inlet pressure can cause the compressors to surge, in which the pressure ratio is 1 and the flow is near zero. Surging compressors vibrate very severely, and quickly deblade, ending their pumping ability. Therefore, with the exception of UF_6 in the tie-lines, no additional amount of UF_6 is expected to be released from the tie-line failure.

R-114 Coolant

A typical '00' cell has a coolant (R-114) volume of 740 ft³ (21 m³). Liquid R-114 fills about 260 ft³ (7.4 m³), while R-114 vapor fills the remaining 480 ft³ (13.6 m³). At the power levels we are looking at in the seismic analysis, the coolant temperature is normally around 150 °F (339 K). Selected thermal properties of R-114 at 150 °F (339 K) and saturated conditions are given below :

Liquid Vapor Pressure = 96.0544 psia (662.3 kPa)

Vapor Specific Volume = 0.335811 ft³/lb (0.021 m³/kg)

Vapor specific heat capacity = 0.194472 BTU/lb-°F (0.8142 kJ/kg-°C)

Sat. Liquid Density = 82.3820 lb/ft³ (1,319.7 kg/m³)

Sat. Vapor Density = 2.97787 lb/ft³ (47.7 kg/m³)

With density values given above, an R-114 inventory is determined as :

- Vapor: 480 ft³ (13.6 m³) x 2.97787 lb/ft³ (47.7 kg/m³) = 1,429.4 lb. (648.4 kg) 6.3 wt. %
(UF_6 mass/R-114 mass = 0.56 for 2,200 MW case & 0.36 for 1,600 MW case)
- Liquid: 260 ft³ (7.4 m³) x 82.3820 lb/ft³ (1,319.7 kg/m³) = 21,419.3 lb. (9,715.6 kg) 93.7 wt. %
- Total R-114 Inventory, per '00' cell = 22,848.7 lb. (10,364 kg)

3. UF_6 RELEASE IMMEDIATELY AT THE BREAK

It was assumed that UF_6 gas is released into the building atmosphere immediately after the pipe breaks following the building collapse due to the seismic event. The released UF_6 gas interacts with moisture in the air to form UO_2F_2 and HF which disperse into the air.

3.1 Method of Approach

The MELCOR code was used to evaluate UO_2F_2 and HF dispersion into the air with following assumptions.

- UF_6 vapor is assumed to be released quickly (for present study assumed to be over 10 seconds).
- UF_6 vapor is assumed to undergo instantaneous reaction with moisture in the air.
- The size of mixing volume is assumed to stay constant.
- Thermal equilibrium is assumed in the mixing volume.
- R-114 liquid is assumed to be stratified at the bottom and not to be available to thermally interact with vapor mixture.
- Water from the fire protection system and reactor coolant system is not considered.
- Lubricant oil fire is absent.
- UF_6 , air and R-114 are assumed to be perfectly mixed. Therefore, its mixing volume is evaluated as :

for 2,200 MW case,

(1) UF_6 vapor volume

$$\text{total inventory released, } m_{\text{UF}_6} = \frac{63,911 \text{ lbs}}{80 \text{ cells}} = 363 \text{ kg / cell}$$

$$V_{\text{UF}_6} = \frac{m_{\text{UF}_6}}{\rho_{\text{UF}_6}} = \frac{363 \text{ kg / cell}}{9.6 \text{ kg / m}^3} = 37.38 \text{ m}^3 / \text{cell} \quad (1)$$

(2) Air volume

- Air volume is evaluated to have enough moisture content to react all the UF_6 mass assuming 60% of relative humidity.

At 1 atm and 300 K, $p = 760 \text{ mmHg}$, $\rho_{\text{air}} = 1.183 \text{ kg/m}^3$,

& saturated water vapor pressure, $e_s = 31.824 \text{ mmHg}$

The relation between mixing ratio and relative humidity is related as

$$\frac{m_{\text{air}}}{m_{\text{H}_2\text{O}}} = \left(\frac{M_{\text{air}}}{M_{\text{H}_2\text{O}}} \right) \frac{p}{(R.H.)e_s} = \frac{28.96}{18} \frac{760}{(0.6)(31.824)} = 64 \quad (2)$$

where M_{air} = molecular weight of dry air (28.96 kg/mole)

$M_{\text{H}_2\text{O}}$ = molecular weight of water vapor (18 kg/mole)

R.H. = relative humidity (60 %)

H₂O mass required to react with 363 kg of UF₆ is determined to be 37.13 kg.

Thus,

$$V_{air} = \frac{m_{air}}{\rho_{air}} = \frac{64 m_{H_2O}}{\rho_{air}} = \frac{(64)(37.13) \text{ kg}}{1.183 \text{ kg/m}^3} = 2,008.45 \text{ m}^3 \quad (3)$$

(3) R-114 vapor volume

$$V_{R114} = 480 \text{ ft}^3 = 13.6 \text{ m}^3$$

Therefore, total mixing volume is 2,059.83 m³

for 1,600 MW case, mixing volume is similarly calculated to be 1,333.06 m³.

- Mixing volume height is evaluated per cell basis assuming that the mixture is uniformly distributed. Since the floor area of one building is 640 ft x 804 ft (195.1 m x 245.1 m) (per 40 cells), each cell area will be (195.1) (245.1) / (40 cells) = 1,195 m². Therefore, mixing height is determined to be 1.724 m and 1.116 m for 2,200 MW and 1,600 MW cases, respectively.
- Since MELCOR does not recognize R-114, its volume is assumed to be occupied by the air. Consequently, MELCOR evaluated mixing temperature will be higher than the actual temperature. In order to supplement the MELCOR calculated mixing temperature, a steady state mixing temperature is externally evaluated (for estimating the plume temperature rise) as

$$\bar{T} = \frac{(m c_p T)_{R114} + (m c_p T)_{air} + m_{UF_6} \dot{H}_R}{(m c_p)_{R114} + (m c_p)_{UO_2F_2} + (m c_p)_{HF} + (m c_p)_{air}} \quad (4)$$

where $\dot{H}_R$ is chemical reaction energy of UF₆ with moisture.

In the MELCOR model, one mixture volume is assumed to be connected to a large control volume representing the environment. Aerosol particles are assumed to be a log-normal distribution between 0.4 μm and 2.5 μm.

3.2 Results and Discussion

The mixing temperature using Eq. (4) are shown in Figures 1 and 2. Figure 1 shows the temperature of R-114, UO_2F_2 , HF and air mixture as a function of the UF_6 mass for various magnitude of R-114 mass mixed in the volume. The mixing temperature is shown again in Fig.2, as a function of mass ratio of UF_6 to R-114. As mentioned above, the mass ratio is 0.56 and 0.36 for 2,200 MW and 1,600 MW, respectively. Corresponding mixing temperature can be obtained as 385 K and 372 K for 2,200 MW and 1,600 MW, respectively. Since the air temperature was assumed to be 300 K, these temperatures represent 85 K and 72 K of temperature increase.

The magnitude of UO_2F_2 and HF mass dispersed into the atmosphere and their temporal variations for 2,200 MW and 1,600 MW cases are shown in Figures 3 and 4. Also shown in the same figures, are the variations of UO_2F_2 aerosol and HF vapor mass in the mixing volume. As seen in the figure, the dispersion (or release) can be characterized as initial pop release followed by a reduced rate of dispersion over a long period of time. The amount of UO_2F_2 dispersed from the mixture volume shown in Figures 3 and 4, represents 63% and 62% of total UO_2F_2 mass for 2,200 MW and 1,600 MW case, respectively. A substantial amount of HF vapor mass is shown to remain in the mixture volume for a long period of time because of lack of enough buoyancy at later time to disperse it out. Since all the building structures are assumed to collapse, however, this undisturbed HF vapor may be dispersed because of atmospheric condition such as wind.

UO_2F_2 aerosols and HF vapor will not be confined within the mixing volume, nor limited from volume expansion. As soon as they are generated, they will be exposed to the atmospheric condition for dispersion while they get settled due to the gravitational force. To obtain an indication of the importance of gravitational settling during the release, the MELCOR calculations were repeated with a single closed volume to observe the trend of gravitation settling (closed volume case versus open volume case that was mentioned above). Since no environmental volume is connected to the mixing volume, we expect to have 100% of UO_2F_2 aerosols to settle down onto the floor eventually. These results are shown in Figures 5 and 6 for 2,200 MW and 1,600 MW case, respectively. As seen in the figures, about 61% (195 kg for 2,200 MW case and 126 kg for 1,600 MW case) of UO_2F_2 aerosols is predicted to settle down onto the floor for the first 200 s of period, and another 25% settles down for next 300 s. The remaining 14% gets settled down eventually for a

long period of time. Therefore, UO_2F_2 mass settled on the floor can be somewhere between values predicted for open volume and for closed volume, as shown in Figures 7 and 8. The settled mass can vary between two curves in the same figures, depending on atmospheric conditions.

However, if lubricant oil fire occurs in the building, it is assumed that all of UO_2F_2 and HF are released into the environment immediately. This is because strong turbulence induced by flames must exist to prevent the stagnation of vapor or settlement of aerosol particles on the ground.

4. UF_6 RELEASE FROM CONVERTERS

An analysis has been performed to assess the UF_6 release from a converter with ruptured nozzles with and without lubricating oil pool fires. During a seismic event, inlet and outlet piping of converters may break with the converter itself remaining intact. Since processing lines are operated under atmospheric pressure, little of UF_6 gases would be released.

When these pipes are opened to the atmosphere, air will rush in both the inlet and outlet nozzles, bringing the pressure up to 1 atmosphere. UF_6 gas should be stratified within the converter bottom, and overflow through the break. Consequently, the level of UF_6 should be stabilized at the neck of nozzles. The amount of subsequent release is slow because the mass transfer rate of UF_6 is determined by a diffusion-controlled process at the interface between the UF_6 and the air above it. An exothermic chemical reaction takes place when the diffusing UF_6 reacts with moisture in air to produce UO_2F_2 aerosols and HF gas, releasing heat of reaction of about 0.32 MJ/kg of UF_6 reacted. During the accident, only HF gas is allowed to release out of converters and UO_2F_2 aerosols would be trapped within the converters because of their complicated internal structures. The diffusion/reaction process continues until the UF_6 gas is depleted.

On the contrary, if the collapse of the buildings causes lubricant oil to burn, a rapid initial UF_6 release would occur as a result of the volume expansion caused by hot flame temperatures. Depending on the degrees of flame temperatures, a significant release of HF can occur initially. After this rapid spill, the release rate will decrease to a much slower diffusion-controlled process.

The objective is to determine the initial rapid HF gas release, the slow diffusion-controlled release, and the release period to depletion of UF_6 gas.

4.1 Converter Data

The equipment type of interest consists of 400 A-line cooled size 00 converters with the following physical characteristics: a length of 221 in (5.61 m), a straight diameter of 90 in (2.286 m), a bulge diameter of 105 in (2.667 m), an inlet nozzle diameter of 42 3/16 in (1.072 m), an A-outlet nozzle diameter of 36 in (0.914 m), a B-outlet nozzle diameter of 24 in (0.61 m), and an internal volume of 806 ft^3 (22.82 m^3). At both 2200 and 1600 MW operations, the pooled inventory remaining in converters is 59,589 lb. (27,029 kg) of UF_6 with an average process gas temperature running at 260 $^{\circ}\text{F}$ (400 K).

4.2 Method of Approach

Since the case without oil burning is a special case, it is necessary only to describe the calculation procedure once. As mentioned, in the presence of lubricant oil burning, the physical process involves two phases: a rapid initial UF_6 release controlled by the flame temperature, followed by a diffusion-controlled slow process. To start calculations, a flame temperature is assigned. Once the oil burning was ignited, it is reasonable to assume the converter is in thermal equilibrium with the flame; specifically, the converter wall temperature, the bulk mixture temperature and the flame temperature are assumed to be the same. When the states of UF_6 are known, the volume expansion can be computed. Based on converter geometry, the amount of UF_6 being spilled can be estimated from the excess volume. Consequently, the amount of pooled UF_6 gas within the converter can be determined.

After this rapid UF_6 spill, the release rate decreases as the diffusion-controlled mass transfer mechanism takes over at the interface between the UF_6 pool and the air above it. The rate of mass transfer depends on the mass diffusion in gases, mass transfer coefficients, concentration gradients, and the interface area. In the calculations, all HF gas generated is assumed to escape from nozzles without choking. So long as the process is pseudo steady-state, the time interval for HF depletion can be calculated from information of the pooled inventory and mass transfer rate.

(A) Initial Rapid Release from a Converter

In this simplified approach, the release process was assumed to consist of two independent steps. Step one involved a volume expansion from an initial stage to a final stage while keeping the pressure and mass constant. Step two involved a release of UF_6 gas corresponding to the amount of volume excess.

Initial UF_6 conditions:

For UF_6 gas pooled inventory per converter,

$$m_{\text{UF}_6} = \frac{m_{\text{UF}_6, \text{total}}}{\text{total number of converters}} = \frac{59,589 \text{ lb}}{400} = 148.97 \text{ lb (67.57 kg)} \quad (5)$$

Pressure inside the converter is assumed to be equilibrated with the outside as atmospheric pressure, and initial process gas temperature (T_i) is 260 °F. Density of UF_6 gas at this thermal condition is to be 0.6 lb/ft³ (9.6 kg/m³). Based on mass inventory and density, the initial volume is calculated as

$$V_i = \frac{m_{\text{UF}_6}}{\rho_{\text{UF}_6}} = \frac{148.97}{0.6} = 248.29 \text{ ft}^3 (7.03 \text{ m}^3) \quad (6)$$

Final UF_6 conditions:

Assuming that the UF_6 is an ideal gas, then under the constant pressure process, the final volume is calculated by:

$$\frac{V_f}{V_i} = \frac{T_f}{T_i} \quad (7)$$

where T_f is UF_6 gas temperature after expansion due to temperature increase followed by lubricant oil fire. The amount of UF_6 release (spill) due to volume expansion is given by:

$$m_{UF6, released} = m_{UF6} \left(1 - \frac{T_i}{T_f} \right) \quad (8)$$

and the pooled UF_6 inside the converter is given by:

$$m_{UF6, pooled} = m_{UF6} \left(\frac{T_i}{T_f} \right) \quad (9)$$

From the stoichiometric relation, HF mass is related as

$$m_{HF} = m_{UF6} \left(\frac{4 M_{HF}}{M_{UF6}} \right) \quad (10)$$

where

M_{HF} = 20 lb/mole, molecular weight of HF gas,

M_{UF6} = 352 lb/mole, molecular weight of UF_6 gas,

m_{HF} = mass of HF gas (lb),

m_{UF6} = mass of UF_6 gas (lb),

T_i = initial gas temperature in Rankin, and

T_f = final gas temperature in Rankin.

(B) Slow Diffusion -Controlled Process at the Interface

Gilliland (Ref. 1) suggested an empirical equation based on published experimental data to obtain the diffusion coefficient as a function of the molecular properties of the diffusing gases:

$$D = 0.0069 T^{3/2} \frac{\left(\frac{1}{M_{air}} + \frac{1}{M_{UF6}} \right)^{1/2}}{p \left(V_{air}^{1/3} + V_{UF6}^{1/3} \right)^2} \quad (11)$$

where

D = diffusivity, ft^2/hr ,

M_{air} = 28.95 lb/mole, molecular weight of air,

p = pressure, atm.,

T = temperature, Rankin,

V_{air} = 29.9, atomic volume of air, and

$V_{\text{UF}_6} = 27.92 + 6 \times 8.7 = 80.12$, atomic volume of UF_6 gas.

Equation (11) should be used only as an approximation where experimental data are not available. Note that $D \sim T^{3/2}$, whereas actually in experimental results $D \sim T^2$ is usually found. The diffusivity was used to calculate the Schmidt number to be defined latter.

No data on mass transfer exist for this process, but by analogy to heat and momentum transfer, the following empirical equations proposed by Chilton and Colburn (Ref. 1) in turbulent flow systems hold:

$$j_D = h_D \frac{Sc^{2/3}}{u} \quad (12)$$

and

$$j_H = j_D = \frac{0.037}{Re_L^{0.2}} \quad (13)$$

where

h_D = mass transfer coefficient, ft/s ,

j_D = Chilton-Colburn j factor for the mass transfer,

j_H = Chilton-Colburn j factor for the heat transfer,

Re_L = Reynolds number based on a flat plate length of L ft,

$Sc = \nu / D$, Schmidt number

u = air velocity, ft/s

Assuming that the UF_6 behaves as an ideal gas, its concentration at the interface can be calculated by

$$C_o = \frac{p M_{UF6}}{RT_f} \quad (14)$$

where

C_o = concentration (lb/ft³),

R = universal gas constant = 1544, if p in lb_f/ft², T in Rankin, M_{UF6} in lb/mole.

The mass transfer rate at the interface within the converter is given by

$$\dot{m}_{UF6} = A h_D (C_o - C_\infty) \quad (15)$$

where

A = interface area = $\pi d^2 / 4 = \pi (105 / 12)^2 / 4 = 60.13 \text{ ft}^2 (5.59 \text{ m}^2)$,

C_o = concentration at the interface (lb/ft³),

C_∞ = concentration at infinity (lb/ft³).

In the calculations using Eq. (15), the concentration at the interface was calculated as a function of temperature but the concentration at infinity away from the interface was assumed to be negligible (i.e., $C_\infty = 0$). In addition, Equations (12) and (13) were combined to calculate h_D , which was then used in Eq. (15) for computing mass transfer rate.

4.3 Results and Discussion

In the presence of lubricant oil burning, the initial UF_6 gas release is a function of the flame temperature (see Table 1). At a flame temperature of 1,700 °F (1,200 K), the volume of UF_6 gas is expanded by a factor of 3. Since the initial UF_6 level is assumed to be at the neck of the converter, any excess volume is released to the atmosphere through the breaks. As a result, two-thirds of UF_6 is released while one-third is left inside the converter. Also, because pressure is kept constant at the atmospheric pressure during this process, the UF_6 density is decreased by a factor of 3. Hence the pooled inventory is one-third of the initial UF_6 mass.

In the absence of lubricant oil burning, parameters related to the diffusion-controlled process at the interface are also functions of temperature as shown in Table 2. Both

kinematic viscosity and diffusivity increase with increasing temperature; however, the Schmidt number (defined as the ratio between the kinematic viscosity and the diffusivity) remains about the same. The Reynolds numbers were calculated using an assumed air velocity of about 3 ft/s (0.91 m/s) and a characteristic length of 105 in (2.667 m) (the longest diameter of the converter). Within the temperature range of interest, the flow was turbulent as indicated by the Reynolds numbers, leading to a more effective diffusion. The mass transfer rate is a product of mass transfer (h_D) and the concentration at the interface (C_o), which have compensating effects. Even though the mass transfer coefficient increases slightly with the increasing temperature, but the opposite is true for the concentration at the interface. As a result, the mass transfer rate at the interface decreases as the temperature rises. The release period to depletion (defined as the ratio between the pooled inventory and the mass transfer rate) did not differ too much for both the absence (9.14 min) and presence (6~7 min) of lubricant oil burning. This is because when the pooled inventory is high at a low temperature, mass transfer becomes more effective.

The release period of residual UF_6 is plotted in Figure 9 for several different values of air/ UF_6 vapor velocity. Certainly, it shows that the release period varies as the vapor velocity changes. However, the period still remains in the same order of magnitude (e.g., ~5 to 10 min at 2,000K)

5. SUMMARY AND CONCLUSIONS

The '00' buildings are expected to collapse during a seismic event in which acceleration level exceeds 0.15g. A simplistic approach was taken to evaluate source term magnitude followed by a process piping break during such an event. Any UF_6 vapor mass is assumed to be released through the break immediately after the pipe break. This UF_6 vapor mixes with air to form a cloud and chemically react with moisture in the air. A resulting product, UO_2F_2 , is subjected to settle down on the ground due to gravity, and to disperse through the air. The magnitude of UO_2F_2 aerosols to be settled onto the ground was estimated to be between about 32% (100 kg / 317.6 kg) and 95% (300 kg / 317.6 kg) for a period of 1,000s, as seen in Figure 7 for 2,200 MW case. For 1,600 MW, Figure 8 shows that about 34% (70 kg / 204.8 kg) to 93% (190 kg / 204.8 kg) of UO_2F_2 aerosols was predicted to be settled over about the same period. However, if a large fire occurs in the building (possibly induced by lubricant oil fire), aerosols are not possible to settle due to strong

buoyancy caused by large flames, and thus all the masses must be released and mixed with air to disperse through the environment.

Substantial UF_6 mass is expected to remain inside the converters at the pipe break. Its release is diffusion-controlled at the interface of this stagnating UF_6 vapor pool and the air above it. If the converter becomes hot due to lubricant oil fire, UF_6 volume must increase, and about 60 to 80% of initial UF_6 mass in the converter was estimated to be released through breaks at the inlet and outlet nozzles. Remaining UF_6 is subjected to slow release controlled by mass diffusion. The study shows that a complete depletion (release) of such a residual UF_6 occurs over about 10 min without lubricant oil fire, and about 6~7 min with the fire.

6. REFERENCES

1. Rohsenow, W.M., and Choi, H. Y., Heat, Mass, and Momentum Transfer, Prentice-Hall, Inc., New Jersey, 1961.

Table 1. UF_6 Volume Expansion, Initial Release, and Pooled Inventory in the Presence of Lubricant Oil Burning as A Function of UF_6 Gas Temperature.

T ($^{\circ}\text{F}$)	T (K)	Vol. Expansion V_r/V_i	Initial UF_6 Release (%)	UF_6 left in converter (%)	UF_6 left in converter (lb)	UF_6 left in converter (kg)
260	400	1.00	0	100	148.97	67.67
300	422	1.06	5	95	141.13	64.02
500	533	1.33	25	75	111.73	50.68
750	672	1.68	40	60	88.64	40.21
1000	811	2.03	51	49	73.47	33.32
1250	950	2.38	58	42	62.73	28.45
1500	1089	2.72	63	37	54.72	24.82
1700	1200	3.00	67	33	49.66	22.52
1800	1255	3.14	68	32	47.46	21.53
1900	1311	3.28	69	31	45.45	20.62
2000	1366	3.42	71	29	43.60	19.78
2500	1644	4.11	76	24	36.24	16.44
3000	1922	4.81	79	21	31.00	14.06

Table 2. Important Parameters Related to the Diffusion-Controlled Process at the Interface Between UF_6 Gas and Air*.

T ($^{\circ}\text{F}$)	T (K)	ν (10^{-4} ft ² /s)	D (10^{-4} ft ² /s)	Sc	Re (10^4)	j_D (10^{-3})	h_D (10^{-3} ft/s)	C_o (lb/ft ³)	$\dot{m}_{\text{UF}_6}$ (lb/s)	$\dot{m}_{\text{UF}_6}$ (kg/s)	Release period (min)
260	400	2.81	1.30	2.16	9.35	3.75	6.74	0.6703	0.2716	0.1232	9.14
300	422	3.08	1.41	2.18	8.53	3.82	6.82	0.6350	0.2603	0.1181	9.04
500	533	4.54	2.00	2.27	5.78	4.13	7.18	0.5027	0.2170	0.0984	8.58
750	672	6.66	2.84	2.35	3.94	4.46	7.57	0.3988	0.1815	0.0823	8.14
1000	811	9.06	3.76	2.41	2.90	4.74	7.91	0.3305	0.1572	0.0713	7.79
1250	950	11.7	4.77	2.46	2.24	4.99	8.22	0.2822	0.1394	0.0632	7.50
1500	1089	14.6	5.85	2.50	1.80	5.22	8.50	0.2462	0.1258	0.0571	7.25
1700	1200	17.1	6.77	2.52	1.54	5.38	8.71	0.2234	0.1170	0.0531	7.07
1800	1255	18.3	7.24	2.53	1.43	5.46	8.81	0.2135	0.1132	0.0513	6.99
1900	1311	19.6	7.73	2.54	1.34	5.53	8.92	0.2045	0.1096	0.0497	6.91
2000	1366	20.9	8.22	2.55	1.25	5.61	9.02	0.1962	0.1064	0.0482	6.83
2500	1644	27.8	10.9	2.56	0.94	5.93	9.51	0.1630	0.0932	0.0423	6.48
3000	1922	34.9	13.7	2.55	0.75	6.21	9.99	0.1395	0.0838	0.0380	6.17

* 0.91 m/s (3 ft/s) of air velocity was assumed.

Figure 1 Temperature of R-114, UO_2F_2 , HF and air mixture as a function of UF_6 mass

Figure 2 Temperature of R-114, UO_2F_2 , HF and air mixture as a function of mass ratio of UF_6 to R-114

Figure 3 UO_2F_2 and HF mass variation for 2,200 MW case

Figure 4 UO_2F_2 and HF mass variation for 1,600 MW case

Figure 5 UO₂F₂ and HF mass variation within a closed volume for 2,200 MW case

Figure 6 UO₂F₂ and HF mass variation within a closed volume for 1,600 MW case

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Figure 9 UF₆ and HF Release Period from Converters

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