Particle Physics Division

Mechanical Department Engineering Note

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COUPP-182

Project: COUPP

Title: **ODH & CF3I Safety Analysis for E-961, COUPP – 60 kg**

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Key Words: ODH, CF3I, safety, COUPP

Abstract/Summary:
This is a formal safety analysis evaluating the ODH risk and CF3I exposure risk posed by operation of the COUPP 60 kg bubble chamber.

Applicable Codes:

Fermilab Environmental, Safety, and Health Manual chapter 5064, Oxygen Deficiency Hazards

American Conference of Governmental Industrial Hygienists (ACGIH) 2005 Threshold Limit Values (TLVs) for Chemical Substances and Physical Agents & Biological Exposure Indices (BEIs) – Minimal Oxygen Content

National Research Council, Committee on Toxicology, Subcommittee on Iodotrifluoromethane, "Iodotrifluoromethane: Toxicity Review". (National Academies Press, 2004)

CF_3I Release Safety Analysis

Outline

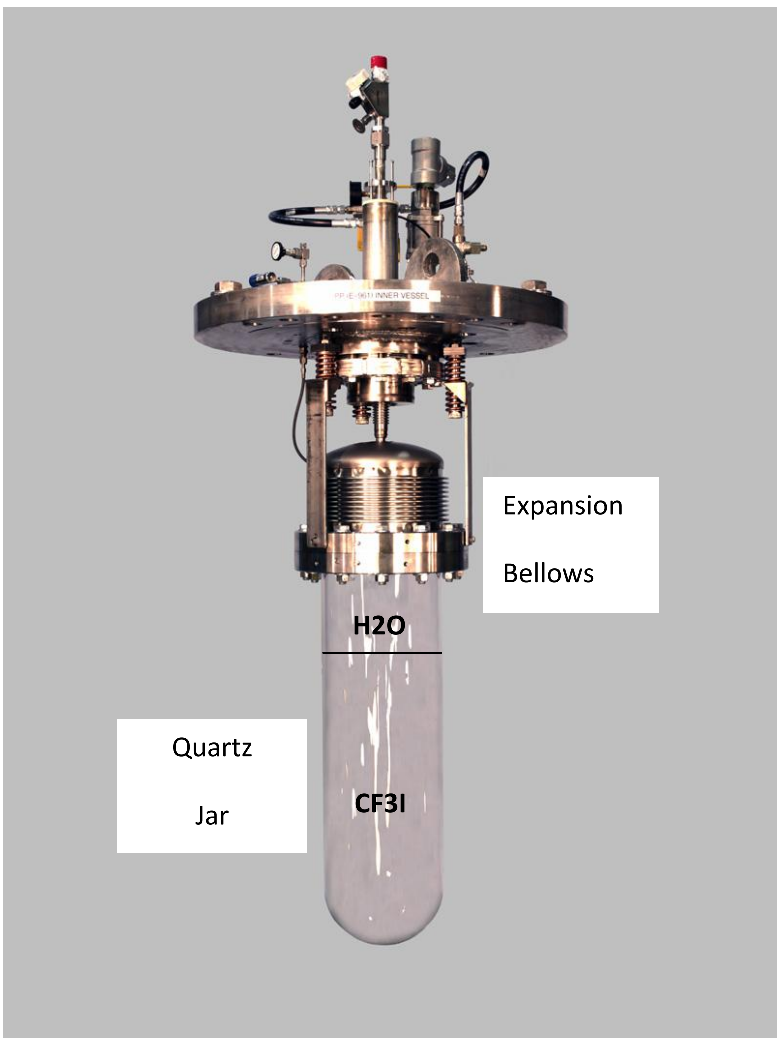
Summary

The analysis definitively shows no risk of ODH from the presence of CF_3I. The empty water tank (confined space) and the MINOS hall are both shown to be ODH class 0. The exposure risk of CF_3I during normal operations and filling is minimal and requires no special precautions.

General Discussion

The COUPP 60 kg bubble chamber will contain up to 80 kg of CF_3I (Trifluormethyl Iodide). CF_3I is a fire extinguishing agent. It is being used for the COUPP experiment because of its nuclear characteristics. It has the right mass for exploring weakly interacting massive particles (WIMPS). One possible safety concern is Oxygen Deficiency Hazard caused by a release of CF_3I. *Another possible safety concern is continuous exposure to CF_3I at levels greater than 0.2% CF_3I in air.*[i] *At CF_3I concentrations greater than 0.2% CF_3I, and for durations longer than a minute, the gas has been shown to lead to cardiac sensitization.*

The sealed volume of the bubble chamber contains about 40 liters of liquid CF_3I and 40 liters of liquid water. The liquid density of the CF_3I is twice that of water so the CF_3I resides in the quartz jar portion of the chamber with water floating on top.



Picture 1. Liquid CF_3I resides in the lower half of the bubble chamber, H_20 in the upper.

The CF_3I is maintained as a liquid because pressure is applied on the dome of the expansion bellows. Propylene glycol surrounds the bubble chamber and is considered the "hydraulic" fluid of the system. See the table below for the anticipated operating conditions.

Table 1. Operating states for the COUPP bubble chamber.

State		Temp (Celcius)	CF3I Pressure (Mpa)	CF3I Density (kg/m^3)	Comments	CF3I Volume (Liters)	CF3I Fixed Mass (kg)	Bellows Position (inches)
1	Fill	1	0.4	2204.7	During fill, condensing	36.00	79.372	-1.86
2	Room temp.	20	0.425	2103.3	Sat. Liquid at 20 C	37.74	79.372	-1.02
3	Operating Temp. - stable	40	0.72985	1992.3	saturated liquid	39.84	79.372	0.01
4	Operating - cocked	40	0.1	1984.3	unstable Liquid ready to boil	40.00	79.372	0.09
5	Operating - midpoint	40	0.8	1993.2	*Bellows at free length	39.82	79.372	0.00
6	Operating - recompression	40	1.5	2002.1	Recompression Pressure	39.64	79.372	-0.09
7	Aux. operating - stable	50	0.9324	1931.4	saturated liquid	41.10	79.372	0.62
8	Aux. operating - cocked	50	0.1	1918.5	unstable Liquid ready to boil	41.37	79.372	0.76
9	Aux. operating - recompression	50	1.5	1940.3	Recompression Pressure	40.91	79.372	0.53
10	Relieving point of outer vessel	40	2.172	2010.6	Compressed liquid	39.48	79.372	-0.17

The vapor density of CF_3I is 8.37 kg/m^3 at 20 C and atmospheric pressure. If the 80 kg of CF_3I is allowed to boil and be released, the volume of gas that will be created is 9.5 m^3.

Safety Analysis – Worst Case analysis

Immediate release of entire contents:

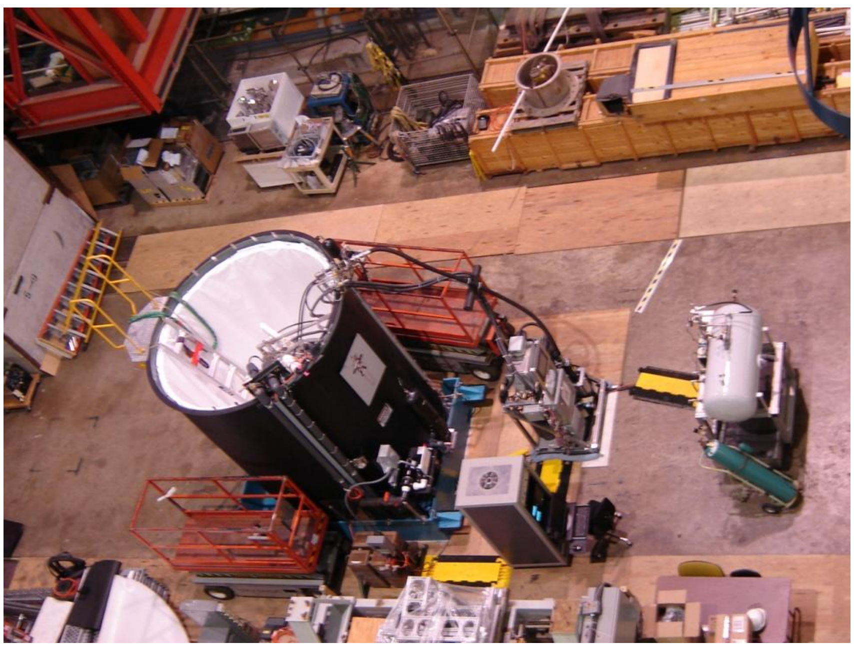
Under normal circumstances, the bubble chamber will be operated in a hot water bath with enclosed light tight tank lid. A release under the water would mean that the CF_3I vapor would inert the tank lid space (about 2.4 m^3) and then spill out the perimeter of the tank. The perimeter of the tank is only roughly sealed for light leak purposes. The tank lid is not gas tight.

The COUPP experiment is currently located in the MINOS hall access tunnel, 350 feet below ground. See picture 2 to see the experiment when it was previously operated in the DZero assembly building during the summer and fall of 2009. The COUPP experiment is sited along the alignment line at station (STA) coordinate "STA 39+50" described on drawing 6-7-6, sheets C-4, A-7, and A-20 of the NUMI Outfitting project 6-7-6. The cross section of the access tunnel can be approximated as 20 feet (6.1 m) wide x 22.5 feet (6.9 m) high. The access tunnel volume starts at approximately STA 37+00 and continues through STA 39+81 (this is 281 feet long) where the tunnel opens up to the MINOS hall.

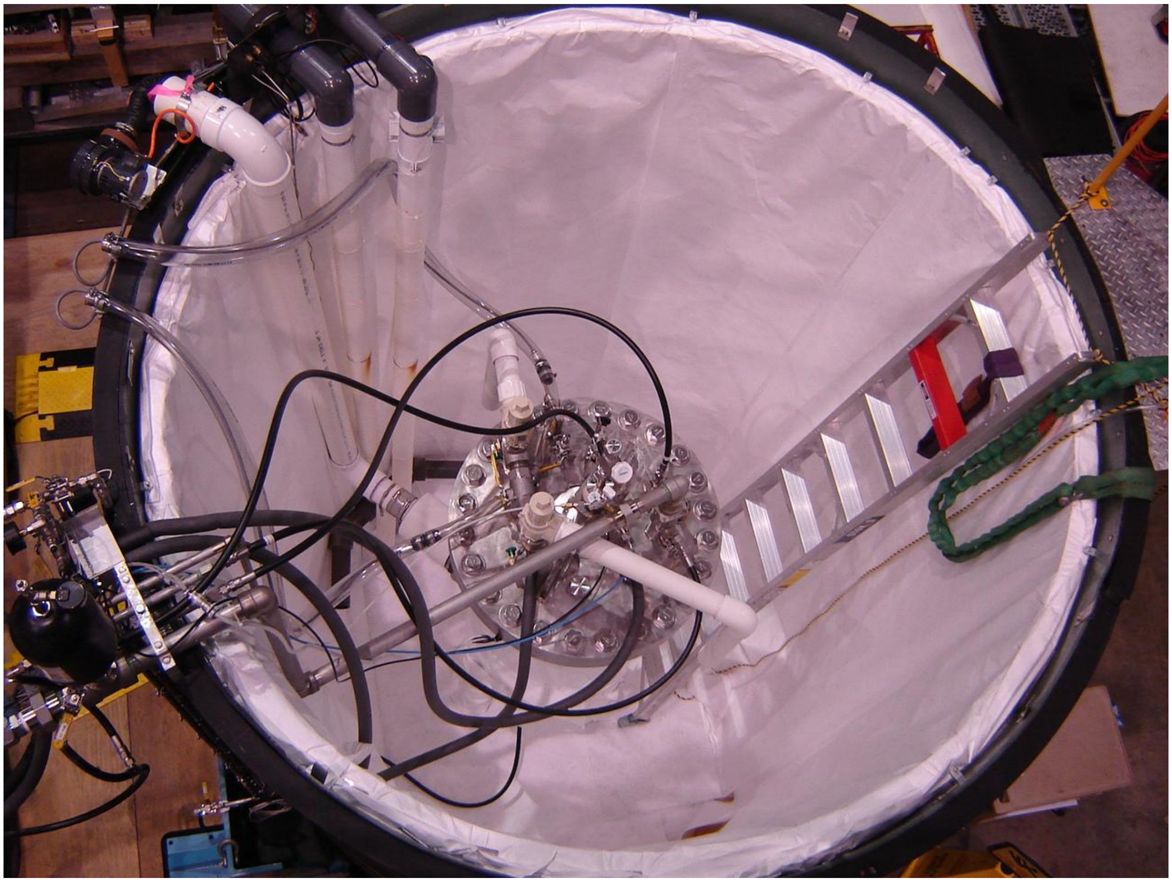
In order to analyze a reasonably sized volume around the COUPP installation, I will consider the volume to be 20 feet upstream and downstream of COUPP. This is a 40 foot (18.2 m) length of tunnel x 20 ft (6.1 m) wide x 22.5 feet (6.9 m) high. The volume of the access tunnel around COUPP then is (6.1 m x 6.9 m x 18.2 m) = 766 m^3 = 27,000 ft^3.

Worst case ODH Analysis in the tunnel: During normal operations, if the total 9.5 m^3 of gas was considered to mix in the volume, then the oxygen concentration would be 0.21 * (383 m^3 – 9.5 m^3) /(383 m^3) = 0.205 = 20.5%. Since the oxygen concentration is nearly normal and greater than 19.5%, the release does not pose an oxygen deficiency hazard. [The mixing assumption is valid since any release rate is turbulent in nature, entraining surrounding air into the stream, quickly diluting the concentration. See Reynolds number and species concentration calculations at the end of this note.] During filling operations, a supply gas cylinder will be present as a source of fluid. The gas cylinder contains the same amount as the bubble chamber during normal operation. Therefore the worst case oxygen concentration possible at any time will be 20.5%.

Worst case CF3I Analysis in the tunnel: If the total 9.5 m^3 of gas was released and mixed in the MINOS access tunnel around COUPP, then the concentration of CF_3I in the space would be 9.5 m^3/766 m^3 = 0.0124 or 1.2% CF_3I. This is above the CF_3I concentration threshold that is conservatively acceptable.



Picture 2. COUPP equipment located in "the Pit" at DZero Assembly building. The vessel resides in the center of the water tank.



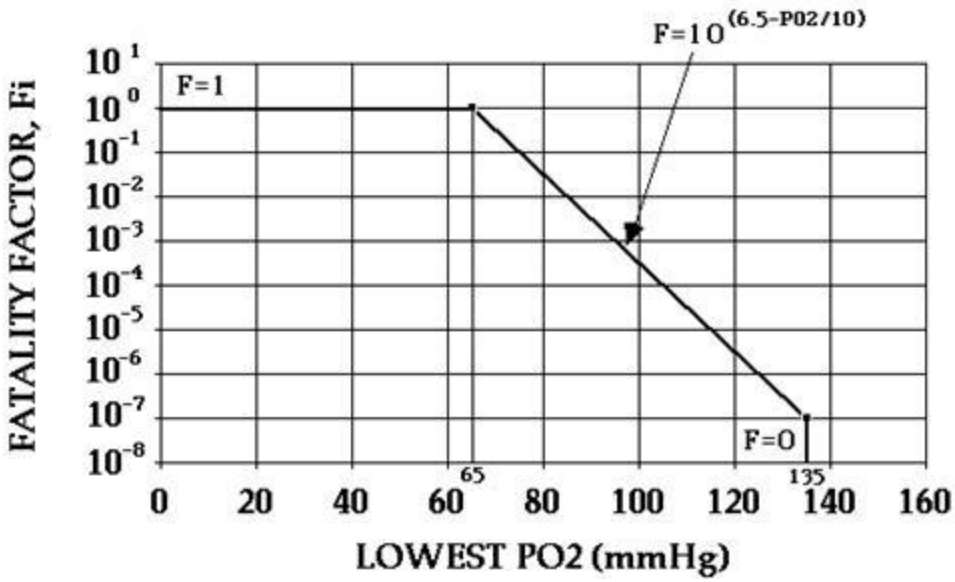
Picture 3. COUPP Outer vessel located inside the 4000 gallon water tank.

Worst case ODH Analysis inside the water tank: If the 9.5 m^3 release occurred in an empty water tank, the CF_3I concentration in the water tank volume (4000 gallon = 15 m^3) could potentially be very high, 63% along with oxygen levels disastrously low, only 7.7%. Therefore a more rigorous analysis is required. During access into the empty tank (with or without CF_3I present) confined space procedures are always followed. This includes active oxygen concentration sampling using a calibrated sensing unit, an unexposed observer, a means for rescue without entry into the tank, forced fresh air ventilation and an approved confined space permit.

Safety Analysis methodology – Traditional analysis

The safety analysis methodology that will be followed is Fermilab's safety and health manual chapter on Oxygen Deficiency Hazards, FESHM 5064 revision May 2009. Sections of this chapter are excerpted below.[ii]

> The oxygen deficiency hazard fatality rate is defined as:
>
> $$\phi = \sum_{i=1}^{n} P_i F_i$$
>
> where $\varnothing$ = the ODH fatality rate (per hour),
>
> P_i = the expected rate of the i^{th} event (per hour), and
>
> F_i = the probability of a fatality due to event i.
>
> The summation shall be taken over all events, which may cause oxygen deficiency and result in fatality. The value of F_i is the probability that a person will die if the i^{th} event occurs. The value depends on the oxygen concentration. If the lowest oxygen concentration is greater than 18%, then the value of F_i is zero, that is, all exposures above 18% are defined to be "safe" and to not contribute to fatality. It is assumed that all exposures to 18% oxygen or lower do contribute to fatality and the value of F_i is designed to reflect this dependence. If the lowest attainable oxygen concentration is 18%, then the value of F_i is 10^{-7}. This value would cause *f* to be 10^{-7} per hour if the expected rate of occurrence of the event were 1 per hour. At decreasing concentrations, the value of F_i should increase until, at some point, the probability of fatality becomes unity. That point was selected to be 8.8% oxygen, the concentration at which one minute of consciousness is expected.



For the ODH analysis that will be made for entry into an empty water tank with CF3I present, the analysis method will be followed directly. The summation of the hazard fatality rate is made and since the result is less than 10^{-7} hr^{-1}, the ODH classification is class 0. The risk is minimized to an acceptable level without special precautions or training.

<u>To evaluate the concern of CF3I exposure</u>, a modification of the terms is made to the analysis.

The CF3I adverse exposure rate is defined as:

$$\mathbf{X} = \sum P_i D_i$$

where **X** = the adverse exposure rate (per hour),

P_i = the expected rate of the i^{th} event (per hour), and

D_i = the probability of an exposure due to event i.

The summation shall be taken over all events, which may cause a release of CF3I and result in an adverse exposure. As was noted in the general discussion, CF3I is an irritant at levels on the order of 0.2%. The 0.2% CF_3I level is considered the no-observed-adverse-effect level (NOAEL) with levels of up to 0.3% acceptable for periods of exposure up to five minutes.[iii] I will call a concentration of 0.2% CF_3I or lower from the i^{th} event equal to a value of D_i of zero. This reasons that an exposure at less than 0.2% is acceptable. An upper threshold of exposure will be set at 0.4%. At this level, critical CF_3I blood concentration for cardiac sensitization was achieved after 51 seconds.[iv] For exposures greater than or equal to 0.4% CF_3I, D_i is equal to unity. I will scale the value of D_i linearly 0.0 to 1.0 for concentrations between 0.2% and 0.4%.

There is no obvious equivalence between CF_3I exposure and ODH classes. What can be said is that exposure to a CF_3I risk is negligible at values less than 0.4%. It is an irritant and cardiac sensitization risk above 0.4%. Momentary (seconds) exposure to higher levels probably would be okay. Standard protocol is to evacuate the area if a large release occurs. The combination of probability of the event and CF_3I levels will need to be determined on a case by case basis.

Table 2. The cases that will be analyzed are:

ODH	Inside empty water tank	Normal operations, sealed BC
CF3I exposure	Inside empty water tank	Normal operations, sealed BC
CF3I exposure	Access tunnel COUPP area	Normal operations, sealed BC
ODH	Inside empty water tank	Batch Fill or Emptying operation
CF3I exposure	Inside empty water tank	Batch Fill or Emptying operation
CF3I exposure	Access tunnel COUPP area	Batch Fill or Emptying operation

Each analysis will be done using the equations entered into a spreadsheet format. Inputs are ventilation rate, tank or access tunnel volume, an enumeration of components and their failure rates and maximum possible leak rate. Outputs are the oxygen or CF_3I concentration with time, ODH fatality rate and ODH classification.

Components, leak rates and probabilities

The components that are in direct contact to the CF_3I bubble chamber volume during normal operation are very limited since it is a sealed volume. There is a section of exposed 1" OD x 0.065" wall stainless steel tube that protrudes out of the lid of the outer vessel. There is one main valve, MV-84, and two other valves, MV-83 and MV-80 connected to the purge port of that main valve. There are a total of 5 VCR connections for these valves and to a pressure transmitter, PT-83. Failure rates are determined from tables in FESHM 5064. The failure rate for rupture of the tube section is $1x10^{-9}$/hr. Valve leak or rupture rates are $1x10^{-8}$/hr. The bellows failure rate is $3x10^{-6}$/hr based on it being equivalent to a flex hose. Connections have failure rates of 3×10^{-6}/hr for a complete rupture or $3x10^{-7}$/hr for a leak. Welds leaking have a failure rate of $3x10^{-6}$/hr. The absolute maximum leak rate possible is bounded by the maximum flow rate that can be achieved up the 1" OD tube during a release. Initially during a release, water would be ejected since it floats on top of the CF_3I. If the hydraulic system was pressurized, four liters of water would be ejected before the stop plate bottomed out and prevented further collapse of the expansion volume bellows. CF_3I would boil at a saturation pressure of 106 psia in the bubble chamber. The maximum flow rate that can be achieved up the tube with 106 psia – 15 psia = 91 psi differential pressure is 684 scfm. This flow rate is limited by the speed of sound in the fluid (106 m/s) and the cross sectional area of the tube. [See calculations at the end of this note] Flow out the main valve is about the same since it is a full ported valve. Flow out the other two valves or any other leaks is limited to a maximum of 29 scfm limited by the cross sectional area of the ¼" OD x 0.035" wall tubing. An obvious (detectable) leaking connection would be equivalent to a 0.020" diameter hole which would flow at 0.2 scfm.

<u>Hydraulic system leak & subsequent CF3I release through ruptured bellows</u>

A loss of pressure in the hydraulic system would cause a pressure differential to develop across the expansion chamber and quartz jar. The large bellows of the expansion chamber is 0.012" thick and is the weakest component in the containment volume. CF_3I would boil to create 3.3 liters of gas which expands the bellows to the end of its allowed travel (+1.625"). A stop plate that is welded to the top of the 1" tube bottoms out against shoulder bolts limiting further bellows travel. The internal pressure in the bubble chamber would be CF_3I saturation pressure, 0.73 MPa, at the operating temperature of 40 C. The quartz jar with wall thickness of 4 mm has an allowable internal working pressure rating of at least 1.4 MPa, so it will not break. The bellows design pressure is 0.3 MPa. The bellows manufacturer, Hyspan, states that a permanent set will not occur at pressures 1.5 times the design pressure or in this case 0.5 MPa.

It would be conservative to assume that the bellows leaks at 0.73 MPa. But assuming that it does, the CF_3I would continue to boil and pass through the bellows leak and then into the propylene glycol space. The CF_3I as a gas would start displacing the propylene glycol volume from the top down. 9.5 m^3 = 9500 liters of CF_3I gas exceeds the entire volume of the propylene glycol volume = 280 liters (74 gallons) so eventually the CF_3I gas would leak out the leak in the hydraulic system. But first, some portion of the propylene glycol would need to leak out and that would be obvious to any observer.

The maximum CF_3I flow rate from a leak through the bellows wall and then through a leak in the hydraulic system can only be based on reasonable speculation. We could speculate for instance that a failure of the bellows into the glycol space would not be catastrophic (large rupture) since the bellows is surrounded by liquid and is made of type 321 stainless steel which is ductile. I can imagine at most a bellows wall crack on the order of 1 mm wide x 5 mm long. A similar sized leak (or larger) in the hydraulic system is required. Based on sonic velocity through that crack, the CF_3I maximum flow rate is 10 scfm. I will use that in my calculations.

<u>Batch fill or batch emptying operations</u>

Special consideration is given to the occasional situation when we are transferring CF_3I to or from the bubble chamber via a transfer line connected to a distillation cart. Extra components of the distillation cart (located outside of the water tank) and transfer line need to be added to the analysis. A knowledgeable operator will be required to open and close valves while observing the mass transfer. Emptying or filling are expected to occur at the frequency of once or twice a year. The transfer line size is on the order of ½" OD tube contained within foam insulation or jacketed by a heating/cooling fluid. The transfer line is connected to filtered ports at the cart and at the bubble chamber. The line is evacuated and then backfilled a number of times. I note that the evacuation pump and backfilling valves are located outside of the tank as part of the distillation cart. As the last step, a valve at the bubble chamber, MV-83 is opened to allow gas transfer. When filling, the distillation vessel at a temperature of 40 Celsius and 0.425 MPa pressure is located outside of the water tank. The bubble chamber is cooled to 1 C and condensation occurs. When emptying, the bubble chamber is at a temperature of 40 C and the container to be transferred to is in an ice bath at 1 C. The extra components are added into the spreadsheets to account for the extra items. There are no vent valves on the transfer line or at the bubble chamber that allow direct venting of the gas. Purity and cleanliness is the hallmark of the experiment. All three connection ports at the bubble chamber are mechanically capped as well as isolated by valves. This precludes a simple "operator error" or "procedural errors" that could lead to a release. The maximum leak rate for a broken transfer line is 17 scfm. This is based on having a high purity carten MD-250 or equivalent valve with flow coefficient of 0.3 at either end of the transfer line.

Ventilation

Active ventilation is provided when accessing the empty water tank. A confined space blower, Allegro Industries part number 9533 is permanently mounted next to the access ladder. It supplies 960 cfm of free air through a 25 foot long, 8" diameter duct. The duct is pulled up and over the tank wall and discharges in the bottom of the tank. The volume of the empty tank is 530 cubic feet so there are roughly two air changes per minute. The MINOS Hall is ventilated by a 4,000 cfm exhaust fan, EF-4, located on the surface drawing air through a shaft at the downstream end of the MINOS hall. This provides the normal HVAC ventilation in the MINOS hall and is on generator backup.

Analysis and Results

The methodology of the traditional analysis was explained earlier in this note. The calculations are done in a spreadsheet format with equations from FESHM 5064. Case A described in the FESHM chapter was most applicable for the tank space. It is a case that assumed mixing and some ventilation input. Below is the pertinent equation excerpted from the chapter:

Case A During release - Ventilation fan(s) blowing outside air into the confined volume. Differential equation for the oxygen mass balance

$$V\frac{dC}{dt} = 0.21Q - (R+Q)C \qquad (1)$$

Solution with the boundary condition of C=0.21 at t=0

$$C(t) = \left(\frac{0.21}{Q+R}\right)\left[Q + R\, e^{-\left(\frac{Q+R}{V}\right)t}\right] \qquad (2)$$

Definitions

C = oxygen concentration

Cr = oxygen concentration during the release

Ce = oxygen concentration after the release has ended

Q = ventilation rate of fan(s), (cfm or m^3/s)

R = spill rate into confined volume, (scfm or m^3/s)

t = time, (minutes or seconds) beginning of release is at t=0

t_e = time when release has ended, (minutes or seconds)

V = confined volume, (ft^3 or m^3)

Some time input is necessary. For analysis inside the empty water tank, I chose to evaluate the concentrations at 0.5 and 1.0 minutes. This is because it takes very little time to exit the tank if something bad occurred. CF3I as an irritant is easily detectable and there is also an active, calibrated air sampling unit monitoring the space as part of confined space entry rules. An unexposed confined space attendant also is present as part of the confined space entry rules. For the case of the 1" tube rupturing, the entire contents of the CF3I is expelled in 0.5 minutes. Therefore for that case, I analyze the concentrations at 0.25 and 0.50 minutes.

Case B described in FESHM chapter 5064 was most applicable for analyzing the access tunnel volume around the experiment. It is a case that assumes mixing and an exhaust ventilation rate. The pertinent equation excerpted from the chapter follows:

Case B During release - Ventilation fans(s) drawing contaminated atmosphere from the confined volume with the ventilation rate greater than the spill rate (Q>R).

Differential equation for the oxygen mass balance

(3) $$V\frac{dC}{dt} = 0.21(Q - R) - QC$$

Solution with the boundary condition of C=0.21 at t=0

(4) $$C(t) = 0.21\left(1 - \frac{R}{Q}\right)\left(1 - e^{-\frac{Q}{V}t}\right)$$

The time input for analysis of the minos access tunnel was chosen to be 5 and 10 minutes. If an event occurred, it may take a little while to discover an issue.

The 0.21 used in the equations is the starting fraction of oxygen. Recognizing this, the same equations can be used to calculate the increasing CF_3I concentration during a release. The 0.21 is replaced by 1.0 so the equation represents the fraction of air during the release. That fraction is subtracted from 1.0 to give the fraction of the inert gas, CF_3I. The formulas used in the ODH and CF_3I analysis spreadsheets are included in their raw format after the analysis spreadsheets.

Table 3. Analysis Results

Type of Analysis	Location	Operational condition	Worst case % O_2 or %CF_3I	Ø or χ Summation (per hour)	Class
ODH	MINOS tunnel by COUPP	Normal or Filling operations	Min. O_2 = 20.5 % (release of all 80 kg)	Not applicable	ODH class 0
ODH	Inside empty water tank	Normal operation	Min. O_2 = 14.1 % (1" tube severed) O_2 > 20.5% all other cases	Ø = $1x10^{-13}$	ODH class 0
CF_3I exposure	Inside empty water tank	Normal operation	Max. CF_3I = 33 % (1" tube severed) CF_3I < 2.5% all other cases	χ = $1.6x10^{-5}$	A chance of 2.5% exposure every 60,000 hours worked
CF_3I exposure	MINOS tunnel by COUPP	Normal operation	Max. CF_3I = 1.3 % (1" tube severed) CF_3I < 0.6% all other cases	χ = $4.6x10^{-6}$	negligible chances of exposure, low concentrations
ODH	Inside empty water tank	Batch Fill or Emptying	Min. O_2 = 14.1 % (1" tube severed) O_2 > 20.5% all other cases	Ø = $1.4x10^{-13}$	ODH class 0
CF_3I exposure	Inside empty water tank	Batch Fill or Emptying	Max. CF_3I = 33 % (1" tube severed) CF_3I < 2.5% all other cases	χ = 1.9×10^{-5}	A chance of 2.5% exposure every 50,000 hours worked
CF_3I exposure	MINOS tunnel by COUPP	Batch Fill or Emptying	Max. CF_3I = 1.3 % (1" tube severed) CF_3I < 0.6% all other cases	χ = $1.6x10^{-5}$	negligible chances, low concentrations

Conclusion

As can be seen in table 3, and earlier arrived at in the worst case bounding analysis, ODH is not a concern. CF_3I exposure is a minor concern, for entry into the empty water tank during normal operations or during filling operations. This type of entry might occur a dozen times during the initial phase of operations. Propylene glycol high point bleed valves on the outer vessel will need to be manipulated during de-gassing operations. There may also be a need to access the camera enclosure and cameras. Precautions that will be taken are: a.) minimum 950 cfm air input into the tank by forced ventilation b.) confined space procedures.

APPENDIX

The spreadsheet calculative analysis cases that follow are:

ODH	Inside empty water tank	Normal operations, sealed BC
CF3I exposure	Inside empty water tank	Normal operations, sealed BC
CF3I exposure	Access tunnel COUPP area	Normal operations, sealed BC
ODH	Inside empty water tank	Batch Fill or Emptying operation
CF3I exposure	Inside empty water tank	Batch Fill or Emptying operation
CF3I exposure	Access tunnel COUPP area	Batch Fill or Emptying operation

ODH analysis Inside Empty Water Tank

Normal operations, bubble chamber isolated

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Air Input	Q	TC, min.	V/Q	
950	cfm	0.56		
Volume	**V**	**Elevation**		**Pressure**
530	ft^3	700 ft		742 mmHG

ITEM	TYPE	N	P FAIL RATE	GROUP FAIL RATE	R leak rate	Q/R LEAK/VENT	Time (t1) min.	fO2{t1} FRACT O2	Time (t2) min.	fO2{t2} FRACT O2	F (t2) Fatal. Factor	Ø Fatal. Rate	ODH Class
BC 1" tube	Bubble Ch.	1	1.00E-09	1.00E-09	684	0.7200	0.25	16.28%	0.50	14.09%	2.67E-06	2.67E-15	0
BC 1" Valve	Bubble Ch.	1	1.00E-08	1.00E-08	684	0.7200	0.25	16.28%	0.50	14.09%	2.67E-06	2.67E-14	0
BC Valves	Bubble Ch.	2	1.00E-08	2.00E-08	29	0.0305	0.50	20.62%	1.00	20.48%	1.59E-09	3.17E-17	0
BC Bellows	Bubble Ch.	1	3.00E-06	3.00E-06	29	0.0305	0.50	20.62%	1.00	20.48%	1.59E-09	4.76E-15	0
Conn. rupture	Bubble Ch.	5	3.00E-07	1.50E-06	29	0.0305	0.50	20.62%	1.00	20.48%	1.59E-09	2.38E-15	0
Conn. leak	Bubble Ch.	5	3.00E-06	1.50E-05	0.2	0.0002	0.50	21.00%	1.00	21.00%	8.40E-10	1.26E-14	0
Instruments	Bubble Ch.	1	1.00E-08	1.00E-08	29	0.0305	0.50	20.62%	1.00	20.48%	1.59E-09	1.59E-17	0
Welds	Bubble Ch.	6	3.00E-09	1.80E-08	29	0.0305	0.50	20.62%	1.00	20.48%	1.59E-09	2.86E-17	0
Pipes	hydraulic	5	1.00E-09	5.00E-09	10	0.0105	0.50	20.87%	1.00	20.82%	1.04E-09	5.22E-18	0
Elbows	hydraulic	10	3.00E-07	3.00E-06	10	0.0105	0.50	20.87%	1.00	20.82%	1.04E-09	3.13E-15	0
Tees	hydraulic	4	3.00E-07	1.20E-06	10	0.0105	0.50	20.87%	1.00	20.82%	1.04E-09	1.25E-15	0
Valves	hydraulic	10	1.00E-08	1.00E-07	10	0.0105	0.50	20.87%	1.00	20.82%	1.04E-09	1.04E-16	0
Connections	hydraulic	20	3.00E-06	6.00E-05	10	0.0105	0.50	20.87%	1.00	20.82%	1.04E-09	6.27E-14	0
Hoses	hydraulic	4	3.00E-06	1.20E-05	10	0.0105	0.50	20.87%	1.00	20.82%	1.04E-09	1.25E-14	0
Instruments	hydraulic	0	1.00E-08	0.00E+00	10	0.0105	0.50	20.87%	1.00	20.82%	1.04E-09	0.00E+00	0
	TOTAL											**1.29E-13**	**0**

CF3I analysis Inside Empty Water Tank

Normal operations, bubble chamber isolated

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Air Input	Q	TC, min.	V/Q	
950	cfm	0.56		
Volume	**V**	**Elevation**		**Pressure**
530	ft^3	700 ft		742 mmHG

ITEM	TYPE	N	P FAIL RATE	GROUP FAIL RATE	R leak rate	Q/R LEAK/VENT	Time (t1) min.	fCF3I{t1} FRACT CF3I	Time (t2) min.	fCF3I{t2} FRACT CF3I	D(t2) Exposure Factor	X Exp. Rate
BC 1" tube	Bubble Ch.	1	1.00E-09	1.00E-09	684	0.7200	0.25	22.49%	0.50	32.90%	1.00	1.00E-09
BC 1" Valve	Bubble Ch.	1	1.00E-08	1.00E-08	684	0.7200	0.25	22.49%	0.50	32.90%	1.00	1.00E-08
BC Valves	Bubble Ch.	2	1.00E-08	2.00E-08	29	0.0305	0.50	1.79%	1.00	2.50%	1.00	2.00E-08
BC Bellows	Bubble Ch.	1	3.00E-06	3.00E-06	29	0.0305	0.50	1.79%	1.00	2.50%	1.00	3.00E-06
Conn. Rupture	Bubble Ch.	5	3.00E-07	1.50E-06	29	0.0305	0.50	1.79%	1.00	2.50%	1.00	1.50E-06
Conn. Leak	Bubble Ch.	5	3.00E-06	1.50E-05	0.2	0.0002	0.50	0.01%	1.00	0.02%	0.00	0.00E+00
Instruments	Bubble Ch.	1	1.00E-08	1.00E-08	29	0.0305	0.50	1.79%	1.00	2.50%	1.00	1.00E-08
Welds	Bubble Ch.	6	3.00E-09	1.80E-08	29	0.0305	0.50	1.79%	1.00	2.50%	1.00	1.80E-08
Pipes	hydraulic	5	1.00E-09	5.00E-09	10	0.0105	0.50	0.62%	1.00	0.87%	1.00	5.00E-09
Elbows	hydraulic	10	3.00E-07	3.00E-06	10	0.0105	0.50	0.62%	1.00	0.87%	1.00	3.00E-06
Tees	hydraulic	4	3.00E-07	1.20E-06	10	0.0105	0.50	0.62%	1.00	0.87%	1.00	1.20E-06
Valves	hydraulic	10	1.00E-08	1.00E-07	10	0.0105	0.50	0.62%	1.00	0.87%	1.00	1.00E-07
Conn. Rupture	hydraulic	20	3.00E-07	6.00E-06	10	0.0105	0.50	0.62%	1.00	0.87%	1.00	6.00E-06
Conn. Leak	hydraulic	20	3.00E-06	6.00E-05	0.2	0.0002	0.50	0.01%	1.00	0.02%	0.00	0.00E+00
Hoses Rupture	hydraulic	4	3.00E-07	1.20E-06	10	0.0105	0.50	0.62%	1.00	0.87%	1.00	1.20E-06
Hoses Leak	hydraulic	4	3.00E-06	1.20E-05	0.2	0.0002	0.50	0.01%	1.00	0.02%	0.00	0.00E+00
Instruments	hydraulic	0	1.00E-08	0.00E+00	0	0.0000	0.50	0.00%	1.00	0.00%	0.00	0.00E+00
	TOTAL											**1.61E-05**

CF3I analysis in Access tunnel by COUPP

Air Exhaust	Q	TC, min.	V/Q	Pressure
4,000	cfm	6.75		
Volume	**V**	**Elevation**		**Pressure**
27,000	ft^3	700 ft		742 mmHG

Normal operations, bubble chamber isolated

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		N	**P**	GROUP	**R**	**Q/R**	Time	fCF3I{t1}	Time	fCF3I{t2}	**D(t2)**	**X**
ITEM	TYPE		FAIL RATE	FAIL RATE	leak rate	LEAK/VENT	(t1) min.	FRACT CF3I	(t2) min.	FRACT CF3I	Exposure Factor	Exp. Rate
BC 1" tube	Bubble Ch.	1	1.00E-09	1.00E-09	684	0.1710	0.25	0.62%	0.50	1.22%	1.00	1.00E-09
BC 1" Valve	Bubble Ch.	1	1.00E-08	1.00E-08	684	0.1710	0.25	0.62%	0.50	1.22%	1.00	1.00E-08
BC Valves	Bubble Ch.	2	1.00E-08	2.00E-08	29	0.0073	5.00	0.38%	10.00	0.56%	1.00	2.00E-08
BC Bellows	Bubble Ch.	1	3.00E-06	3.00E-06	29	0.0073	5.00	0.38%	10.00	0.56%	1.00	3.00E-06
conn. rupture	Bubble Ch.	5	3.00E-07	1.50E-06	29	0.0073	5.00	0.38%	10.00	0.56%	1.00	1.50E-06
conn. leak	Bubble Ch.	5	3.00E-06	1.50E-05	0.2	0.0001	5.00	0.00%	10.00	0.00%	0.00	0.00E+00
instruments	Bubble Ch.	1	1.00E-08	1.00E-08	29	0.0073	5.00	0.38%	10.00	0.56%	1.00	1.00E-08
welds	Bubble Ch.	6	3.00E-09	1.80E-08	29	0.0073	5.00	0.38%	10.00	0.56%	1.00	1.80E-08
Pipes	hydraulic	10	1.00E-09	1.00E-08	10	0.0025	5.00	0.13%	10.00	0.19%	0.00	0.00E+00
Elbows	hydraulic	30	3.00E-07	9.00E-06	10	0.0025	5.00	0.13%	10.00	0.19%	0.00	0.00E+00
Tees	hydraulic	25	3.00E-07	7.50E-06	10	0.0025	5.00	0.13%	10.00	0.19%	0.00	0.00E+00
Valves	hydraulic	50	1.00E-08	5.00E-07	10	0.0025	5.00	0.13%	10.00	0.19%	0.00	0.00E+00
connections	hydraulic	200	3.00E-06	6.00E-04	10	0.0025	5.00	0.13%	10.00	0.19%	0.00	0.00E+00
hoses	hydraulic	7	3.00E-06	2.10E-05	10	0.0025	5.00	0.13%	10.00	0.19%	0.00	0.00E+00
instruments	hydraulic	11	1.00E-08	1.10E-07	10	0.0025	5.00	0.13%	10.00	0.19%	0.00	0.00E+00
	TOTAL											**4.56E-06**

ODH analysis Inside Empty Water Tank

Air Input	Q	TC, min.	V/Q	Pressure
950	cfm	0.56		
Volume	**V**	**Elevation**		**Pressure**
530	ft^3	700 ft		742 mmHG

Batch fill or Batch empty operation

		N	**P**	GROUP	**R**	**Q/R**	Time	fO2{t1}	Time	fO2{t2}	**F (t2)**	**Ø**	**ODH**
ITEM	TYPE		FAIL RATE	FAIL RATE	leak rate	LEAK/VENT	(t1) min.	FRACT O2	(t2) min.	FRACT O2	Fatal. Factor	Fatal. Rate	**Class**
BC 1" tube	Bubble Ch	1	1.00E-09	1.00E-09	684	0.7200	0.25	16.28%	0.50	14.09%	2.67E-06	2.67E-15	0
BC 1" Valve	Bubble Ch	1	1.00E-08	1.00E-08	684	0.7200	0.25	16.28%	0.50	14.09%	2.67E-06	2.67E-14	0
BC Valves	Bubble Ch	4	1.00E-08	4.00E-08	29	0.0305	0.50	20.62%	1.00	20.48%	1.59E-09	6.35E-17	0
BC Bellows	Bubble Ch	1	3.00E-06	3.00E-06	29	0.0305	0.50	20.62%	1.00	20.48%	1.59E-09	4.76E-15	0
Conn. rupture	Bubble Ch	8	3.00E-07	2.40E-06	29	0.0305	0.50	20.62%	1.00	20.48%	1.59E-09	3.81E-15	0
Conn. leak	Bubble Ch	8	3.00E-06	2.40E-05	0.2	0.0002	0.50	21.00%	1.00	21.00%	8.40E-10	2.02E-14	0
Instruments	Bubble Ch	1	1.00E-08	1.00E-08	29	0.0305	0.50	20.62%	1.00	20.48%	1.59E-09	1.59E-17	0
Welds	Bubble Ch	10	3.00E-09	3.00E-08	29	0.0305	0.50	20.62%	1.00	20.48%	1.59E-09	4.76E-17	0
transfer line	CF3I	1	3.00E-06	3.00E-06	17	0.0179	0.50	20.78%	1.00	20.69%	1.22E-09	3.66E-15	0
Pipes	hydraulic	5	1.00E-09	5.00E-09	10	0.0105	0.50	20.87%	1.00	20.82%	1.04E-09	5.22E-18	0
Elbows	hydraulic	10	3.00E-07	3.00E-06	10	0.0105	0.50	20.87%	1.00	20.82%	1.04E-09	3.13E-15	0
Tees	hydraulic	4	3.00E-07	1.20E-06	10	0.0105	0.50	20.87%	1.00	20.82%	1.04E-09	1.25E-15	0
Valves	hydraulic	10	1.00E-08	1.00E-07	10	0.0105	0.50	20.87%	1.00	20.82%	1.04E-09	1.04E-16	0
Connections	hydraulic	20	3.00E-06	6.00E-05	10	0.0105	0.50	20.87%	1.00	20.82%	1.04E-09	6.27E-14	0
Hoses	hydraulic	4	3.00E-06	1.20E-05	10	0.0105	0.50	20.87%	1.00	20.82%	1.04E-09	1.25E-14	0
Instruments	hydraulic	0	1.00E-08	0.00E+00	10	0.0105	0.50	20.87%	1.00	20.82%	1.04E-09	0.00E+00	0
	TOTAL											**1.42E-13**	**0**

CF3I analysis Inside Empty Water Tank

Batch fill or Batch empty operation

Air Input	**Q**	**TC, min.**	**V/Q**	
950	cfm	0.56		
Volume	**V**	**Elevation**		**Pressure**
530	ft^3	700 ft		742 mmHG

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ITEM	TYPE	**N**	**P** FAIL RATE	GROUP FAIL RATE	**R** leak rate	**Q/R** LEAK/VENT	Time (t1) min.	fCF3I{t1} FRACT CF3I	Time (t2) min.	fCF3I{t2} FRACT CF3I	**D(t2)** Exposure Factor	**X** Exp. Rate
BC 1" tube	Bubble Ch.	1	1.00E-09	1.00E-09	684	0.7200	0.25	22.49%	0.50	32.90%	1.00	1.00E-09
BC 1" Valve	Bubble Ch.	1	1.00E-08	1.00E-08	684	0.7200	0.25	22.49%	0.50	32.90%	1.00	1.00E-08
BC Valves	Bubble Ch.	2	1.00E-08	2.00E-08	29	0.0305	0.50	1.79%	1.00	2.50%	1.00	2.00E-08
BC Bellows	Bubble Ch.	1	3.00E-06	3.00E-06	29	0.0305	0.50	1.79%	1.00	2.50%	1.00	3.00E-06
Conn. Rupture	Bubble Ch.	5	3.00E-07	1.50E-06	29	0.0305	0.50	1.79%	1.00	2.50%	1.00	1.50E-06
Conn. Leak	Bubble Ch.	5	3.00E-06	1.50E-05	0.2	0.0002	0.50	0.01%	1.00	0.02%	0.00	0.00E+00
instruments	Bubble Ch.	1	1.00E-08	1.00E-08	29	0.0305	0.50	1.79%	1.00	2.50%	1.00	1.00E-08
welds	Bubble Ch.	6	3.00E-09	1.80E-08	29	0.0305	0.50	1.79%	1.00	2.50%	1.00	1.80E-08
transfer line	CF3I	1	3.00E-06	3.00E-06	17	0.0179	0.50	1.05%	1.00	1.47%	1.00	3.00E-06
Pipes	hydraulic	5	1.00E-09	5.00E-09	10	0.0105	0.50	0.62%	1.00	0.87%	1.00	5.00E-09
Elbows	hydraulic	10	3.00E-07	3.00E-06	10	0.0105	0.50	0.62%	1.00	0.87%	1.00	3.00E-06
Tees	hydraulic	4	3.00E-07	1.20E-06	10	0.0105	0.50	0.62%	1.00	0.87%	1.00	1.20E-06
Valves	hydraulic	10	1.00E-08	1.00E-07	10	0.0105	0.50	0.62%	1.00	0.87%	1.00	1.00E-07
Conn. Rupture	hydraulic	20	3.00E-07	6.00E-06	10	0.0105	0.50	0.62%	1.00	0.87%	1.00	6.00E-06
Conn. Leak	hydraulic	20	3.00E-06	6.00E-05	0.2	0.0002	0.50	0.01%	1.00	0.02%	0.00	0.00E+00
Hoses Rupture	hydraulic	4	3.00E-07	1.20E-06	10	0.0105	0.50	0.62%	1.00	0.87%	1.00	1.20E-06
Hoses Leak	hydraulic	4	3.00E-06	1.20E-05	0.2	0.0002	0.50	0.01%	1.00	0.02%	0.00	0.00E+00
instruments	hydraulic	0	1.00E-08	0.00E+00	0	0.0000	0.50	0.00%	1.00	0.00%	0.00	0.00E+00
	TOTAL											**1.91E-05**

CF3I analysis in Access tunnel by COUPP

Batch fill or Batch empty operation

Air Input	**Q**	**TC, min.**	**V/Q**	
4,000	cfm	6.75		
Volume	**V**	**Elevation**		**Pressure**
27,000	ft^3	700 ft		742 mmHG

ITEM	TYPE	**N**	**P** FAIL RATE	GROUP FAIL RATE	**R** leak rate	**Q/R** LEAK/VENT	Time (t1) min.	fCF3I{t1} FRACT CF3I	Time (t2) min.	fCF3I{t2} FRACT CF3I	**D(t2)** Exposure Factor	**X** Exp. Rate
BC 1" tube	Bubble Ch	1	1.00E-09	1.00E-09	684	0.1710	0.25	0.62%	0.50	1.22%	1.00	1.00E-09
BC 1" Valve	Bubble Ch	1	1.00E-08	1.00E-08	684	0.1710	0.25	0.62%	0.50	1.22%	1.00	1.00E-08
BC Valves	Bubble Ch	2	1.00E-08	2.00E-08	29	0.0073	5.00	0.38%	10.00	0.56%	1.00	2.00E-08
BC Bellows	Bubble Ch	1	3.00E-06	3.00E-06	29	0.0073	5.00	0.38%	10.00	0.56%	1.00	3.00E-06
Conn. Rupture	Bubble Ch	5	3.00E-07	1.50E-06	29	0.0073	5.00	0.38%	10.00	0.56%	1.00	1.50E-06
Conn. Leak	Bubble Ch	5	3.00E-06	1.50E-05	0.2	0.0001	5.00	0.00%	10.00	0.00%	0.00	0.00E+00
Instruments	Bubble Ch	1	1.00E-08	1.00E-08	29	0.0073	5.00	0.38%	10.00	0.56%	1.00	1.00E-08
Welds	Bubble Ch	6	3.00E-09	1.80E-08	29	0.0073	5.00	0.38%	10.00	0.56%	1.00	1.80E-08
transfer line	CF_3I	1	3.00E-06	3.00E-06	17	0.0043	5.00	0.22%	10.00	0.33%	0.64	1.93E-06
Cart tubes	CF_3I	10	1.00E-09	1.00E-08	17	0.0043	5.00	0.22%	10.00	0.33%	0.64	6.42E-09
Cart elbows	CF_3I	10	3.00E-07	3.00E-06	17	0.0043	5.00	0.22%	10.00	0.33%	0.64	1.93E-06
Cart tees	CF_3I	10	3.00E-07	3.00E-06	17	0.0043	5.00	0.22%	10.00	0.33%	0.64	1.93E-06
Cart valves	CF_3I	15	1.00E-08	1.50E-07	17	0.0043	5.00	0.22%	10.00	0.33%	0.64	9.63E-08
Cart connections	CF_3I	30	3.00E-07	9.00E-06	17	0.0043	5.00	0.22%	10.00	0.33%	0.64	5.78E-06
Cart insturments	CF_3I	3	1.00E-08	3.00E-08	17	0.0043	5.00	0.22%	10.00	0.33%	0.64	1.93E-08
Pipes	hydraulic	10	1.00E-09	1.00E-08	10	0.0025	5.00	0.13%	10.00	0.19%	0.00	0.00E+00
Elbows	hydraulic	30	3.00E-07	9.00E-06	10	0.0025	5.00	0.13%	10.00	0.19%	0.00	0.00E+00
Tees	hydraulic	25	3.00E-07	7.50E-06	10	0.0025	5.00	0.13%	10.00	0.19%	0.00	0.00E+00
Valves	hydraulic	50	1.00E-08	5.00E-07	10	0.0025	5.00	0.13%	10.00	0.19%	0.00	0.00E+00
Conn. Rupture	hydraulic	200	3.00E-07	6.00E-05	10	0.0025	5.00	0.13%	10.00	0.19%	0.00	0.00E+00
Conn. Leak	hydraulic	200	3.00E-06	6.00E-04	0.2	0.0001	5.00	0.00%	10.00	0.00%	0.00	0.00E+00
Hoses Rupture	hydraulic	7	3.00E-07	2.10E-06	10	0.0025	5.00	0.13%	10.00	0.19%	0.00	0.00E+00
Hoses Leak	hydraulic	7	3.00E-06	2.10E-05	0.2	0.0001	5.00	0.00%	10.00	0.00%	0.00	0.00E+00
Instruments	hydraulic	11	1.00E-08	1.10E-07	0	0.0000	5.00	0.00%	10.00	0.00%	0.00	0.00E+00
	TOTAL											**1.62E-05**

The raw equations for the ODH analysis are shown in the following two tables.

	A	B	C	D	E	F	G	H	I	J	K	L	
1													
2						ODH analysis Inside Empty Water Tank							
3													
4	Air Input	Q	TC, min.	V/Q		Batch fill or Batch empty operation							
5	950	cfm	=A7/A5										
6	Volume	V	Elevation		Pressure								
7	530	ft^3	700		=760-0.0262*C7+0.000000285*(C7^2)								
8				N	P	GROUP	R	Q/R	Time	fO2{t1}	Time	fO2{t2}	
9	ITEM		TYPE		FAIL RATE	FAIL RATE	leak rate	LEAK/VENT	(t1) min.	FRACT O2	(t2) min.	FRACT O2	
10	BC 1" tube		Bubble Ch.	1	0.000000001	=D10*E10	684	=(G10/$A$5)	0.5	=(0.21/($A$5	1	=(0.21/($A$5+G10)*($A$5+G10*EXP(-($A$5+G10)*K10/$A$7)))	=IF(J10>0.
11	BC 1" Valve		Bubble Ch.	1	0.00000001	=D11*E11	684	=(G11/$A$5)	0.5	=(0.21/($A$5	1	=(0.21/($A$5+G11)*($A$5+G11*EXP(-($A$5+G11)*K11/$A$7)))	=IF(J11>0.
12	BC Valves		Bubble Ch.	4	0.00000001	=D12*E12	29	=(G12/$A$5)	0.5	=(0.21/($A$5	1	=(0.21/($A$5+G12)*($A$5+G12*EXP(-($A$5+G12)*K12/$A$7)))	=IF(J12>0.
13	BC Bellows		Bubble Ch.	1	0.000003	=D13*E13	29	=(G13/$A$5)	0.5	=(0.21/($A$5	1	=(0.21/($A$5+G13)*($A$5+G13*EXP(-($A$5+G13)*K13/$A$7)))	=IF(J13>0.
14	Conn. rupture		Bubble Ch.	8	0.0000003	=D14*E14	29	=(G14/$A$5)	0.5	=(0.21/($A$5	1	=(0.21/($A$5+G14)*($A$5+G14*EXP(-($A$5+G14)*K14/$A$7)))	=IF(J14>0.
15	Conn. leak		Bubble Ch.	8	0.000003	=D15*E15	0.2	=(G15/$A$5)	0.5	=(0.21/($A$5	1	=(0.21/($A$5+G15)*($A$5+G15*EXP(-($A$5+G15)*K15/$A$7)))	=IF(J15>0.
16	Instruments		Bubble Ch.	1	0.00000001	=D16*E16	29	=(G16/$A$5)	0.5	=(0.21/($A$5	1	=(0.21/($A$5+G16)*($A$5+G16*EXP(-($A$5+G16)*K16/$A$7)))	=IF(J16>0.
17	Welds		Bubble Ch.	10	0.000000003	=D17*E17	29	=(G17/$A$5)	0.5	=(0.21/($A$5	1	=(0.21/($A$5+G17)*($A$5+G17*EXP(-($A$5+G17)*K17/$A$7)))	=IF(J17>0.
18	**transfer line**		CF3I	1	0.000003	=D18*E18	29	=(G18/$A$5)	0.5	=(0.21/($A$5	1	=(0.21/($A$5+G18)*($A$5+G18*EXP(-($A$5+G18)*K18/$A$7)))	=IF(J18>0.
19	**operator error**		open valve	3	0.003	=D19*E19	17	=(G19/$A$5)	0.5	=(0.21/($A$5	1	=(0.21/($A$5+G19)*($A$5+G19*EXP(-($A$5+G19)*K19/$A$7)))	=IF(J19>0.
20	Pipes		hydraulic	5	0.000000001	=D20*E20	10	=(G20/$A$5)	0.5	=(0.21/($A$5	1	=(0.21/($A$5+G20)*($A$5+G20*EXP(-($A$5+G20)*K20/$A$7)))	=IF(J20>0.
21	Elbows		hydraulic	10	0.0000003	=D21*E21	10	=(G21/$A$5)	0.5	=(0.21/($A$5	1	=(0.21/($A$5+G21)*($A$5+G21*EXP(-($A$5+G21)*K21/$A$7)))	=IF(J21>0.
22	Tees		hydraulic	4	0.0000003	=D22*E22	10	=(G22/$A$5)	0.5	=(0.21/($A$5	1	=(0.21/($A$5+G22)*($A$5+G22*EXP(-($A$5+G22)*K22/$A$7)))	=IF(J22>0.
23	Valves		hydraulic	10	0.00000001	=D23*E23	10	=(G23/$A$5)	0.5	=(0.21/($A$5	1	=(0.21/($A$5+G23)*($A$5+G23*EXP(-($A$5+G23)*K23/$A$7)))	=IF(J23>0.
24	Connections		hydraulic	20	0.000003	=D24*E24	10	=(G24/$A$5)	0.5	=(0.21/($A$5	1	=(0.21/($A$5+G24)*($A$5+G24*EXP(-($A$5+G24)*K24/$A$7)))	=IF(J24>0.
25	Hoses		hydraulic	4	0.000003	=D25*E25	10	=(G25/$A$5)	0.5	=(0.21/($A$5	1	=(0.21/($A$5+G25)*($A$5+G25*EXP(-($A$5+G25)*K25/$A$7)))	=IF(J25>0.
26	Instruments		hydraulic	0	0.00000001	=D26*E26	10	=(G26/$A$5)	0.5	=(0.21/($A$5	1	=(0.21/($A$5+G26)*($A$5+G26*EXP(-($A$5+G26)*K26/$A$7)))	=IF(J26>0.
27			TOTAL										

	L	M	N	O
7				
8	fO2{t2}	**F (t2)**	**Ø**	**ODH**
9	FRACT O2	Fatal. Factor	Fatal. Rate	Class
10	=(0.21/($A$5+G10)*($A$5+G10*EXP(-($A$5+G10)*K10/$A$7)))	=IF(J10>0.08553,10^(6.5-($E$7/10)*J10),1)	=F10*(M10)	=IF(N10<=0.0000001,0,IF(N10<=0.00001,1,IF(N10<=0.001,2,IF(N10<=0.1,3,4))))
11	=(0.21/($A$5+G11)*($A$5+G11*EXP(-($A$5+G11)*K11/$A$7)))	=IF(J11>0.08553,10^(6.5-($E$7/10)*J11),1)	=F11*(M11)	=IF(N11<=0.0000001,0,IF(N11<=0.00001,1,IF(N11<=0.001,2,IF(N11<=0.1,3,4))))
12	=(0.21/($A$5+G12)*($A$5+G12*EXP(-($A$5+G12)*K12/$A$7)))	=IF(J12>0.08553,10^(6.5-($E$7/10)*J12),1)	=F12*(M12)	=IF(N12<=0.0000001,0,IF(N12<=0.00001,1,IF(N12<=0.001,2,IF(N12<=0.1,3,4))))
13	=(0.21/($A$5+G13)*($A$5+G13*EXP(-($A$5+G13)*K13/$A$7)))	=IF(J13>0.08553,10^(6.5-($E$7/10)*J13),1)	=F13*(M13)	=IF(N13<=0.0000001,0,IF(N13<=0.00001,1,IF(N13<=0.001,2,IF(N13<=0.1,3,4))))
14	=(0.21/($A$5+G14)*($A$5+G14*EXP(-($A$5+G14)*K14/$A$7)))	=IF(J14>0.08553,10^(6.5-($E$7/10)*J14),1)	=F14*(M14)	=IF(N14<=0.0000001,0,IF(N14<=0.00001,1,IF(N14<=0.001,2,IF(N14<=0.1,3,4))))
15	=(0.21/($A$5+G15)*($A$5+G15*EXP(-($A$5+G15)*K15/$A$7)))	=IF(J15>0.08553,10^(6.5-($E$7/10)*J15),1)	=F15*(M15)	=IF(N15<=0.0000001,0,IF(N15<=0.00001,1,IF(N15<=0.001,2,IF(N15<=0.1,3,4))))
16	=(0.21/($A$5+G16)*($A$5+G16*EXP(-($A$5+G16)*K16/$A$7)))	=IF(J16>0.08553,10^(6.5-($E$7/10)*J16),1)	=F16*(M16)	=IF(N16<=0.0000001,0,IF(N16<=0.00001,1,IF(N16<=0.001,2,IF(N16<=0.1,3,4))))
17	=(0.21/($A$5+G17)*($A$5+G17*EXP(-($A$5+G17)*K17/$A$7)))	=IF(J17>0.08553,10^(6.5-($E$7/10)*J17),1)	=F17*(M17)	=IF(N17<=0.0000001,0,IF(N17<=0.00001,1,IF(N17<=0.001,2,IF(N17<=0.1,3,4))))
18	=(0.21/($A$5+G18)*($A$5+G18*EXP(-($A$5+G18)*K18/$A$7)))	=IF(J18>0.08553,10^(6.5-($E$7/10)*J18),1)	=F18*(M18)	=IF(N18<=0.0000001,0,IF(N18<=0.00001,1,IF(N18<=0.001,2,IF(N18<=0.1,3,4))))
19	=(0.21/($A$5+G19)*($A$5+G19*EXP(-($A$5+G19)*K19/$A$7)))	=IF(J19>0.08553,10^(6.5-($E$7/10)*J19),1)	=F19*(M19)	=IF(N19<=0.0000001,0,IF(N19<=0.00001,1,IF(N19<=0.001,2,IF(N19<=0.1,3,4))))
20	=(0.21/($A$5+G20)*($A$5+G20*EXP(-($A$5+G20)*K20/$A$7)))	=IF(J20>0.08553,10^(6.5-($E$7/10)*J20),1)	=F20*(M20)	=IF(N20<=0.0000001,0,IF(N20<=0.00001,1,IF(N20<=0.001,2,IF(N20<=0.1,3,4))))
21	=(0.21/($A$5+G21)*($A$5+G21*EXP(-($A$5+G21)*K21/$A$7)))	=IF(J21>0.08553,10^(6.5-($E$7/10)*J21),1)	=F21*(M21)	=IF(N21<=0.0000001,0,IF(N21<=0.00001,1,IF(N21<=0.001,2,IF(N21<=0.1,3,4))))
22	=(0.21/($A$5+G22)*($A$5+G22*EXP(-($A$5+G22)*K22/$A$7)))	=IF(J22>0.08553,10^(6.5-($E$7/10)*J22),1)	=F22*(M22)	=IF(N22<=0.0000001,0,IF(N22<=0.00001,1,IF(N22<=0.001,2,IF(N22<=0.1,3,4))))
23	=(0.21/($A$5+G23)*($A$5+G23*EXP(-($A$5+G23)*K23/$A$7)))	=IF(J23>0.08553,10^(6.5-($E$7/10)*J23),1)	=F23*(M23)	=IF(N23<=0.0000001,0,IF(N23<=0.00001,1,IF(N23<=0.001,2,IF(N23<=0.1,3,4))))
24	=(0.21/($A$5+G24)*($A$5+G24*EXP(-($A$5+G24)*K24/$A$7)))	=IF(J24>0.08553,10^(6.5-($E$7/10)*J24),1)	=F24*(M24)	=IF(N24<=0.0000001,0,IF(N24<=0.00001,1,IF(N24<=0.001,2,IF(N24<=0.1,3,4))))
25	=(0.21/($A$5+G25)*($A$5+G25*EXP(-($A$5+G25)*K25/$A$7)))	=IF(J25>0.08553,10^(6.5-($E$7/10)*J25),1)	=F25*(M25)	=IF(N25<=0.0000001,0,IF(N25<=0.00001,1,IF(N25<=0.001,2,IF(N25<=0.1,3,4))))
26	=(0.21/($A$5+G26)*($A$5+G26*EXP(-($A$5+G26)*K26/$A$7)))	=IF(J26>0.08553,10^(6.5-($E$7/10)*J26),1)	=F26*(M26)	=IF(N26<=0.0000001,0,IF(N26<=0.00001,1,IF(N26<=0.001,2,IF(N26<=0.1,3,4))))
27			**=SUM(N10:N26)**	**=IF(N27<=0.0000001,0,IF(N27<=0.00001,1,IF(N27<=0.001,2,IF(N27<=0.1,3,4))))**

The raw equations for the CF3I analysis are shown in the following two tables.

CF3I_release_ODH table May_2010rev.xlsx

	A	B	C	D	E	F	G	H	I	J	K	L
1						CF3I analysis Inside Empty Water Tank						
2												
3						Batch fill or E						
4	Air Input	Q	TC, min.	V/Q								
5	950	cfm	=A7/A5				-					
6	Volume	V	Elevation		Pressure							
7	530	ft^3	700		=760-0.0262*C7							
8				N	P	GROUP	R	Q/R	Time	fCF3I{t1}	Time	fCF3I{t2}
9	ITEM		TYPE		FAIL RATE	FAIL RATE	leak rate	LEAK/VENT	(t1) min.	FRACT CF3I	(t2) min.	FRACT CF3I
10	BC 1" tube		Bubble Ch.	1	0.000000001	=D10*E10	684	=(G10/$A$5)	0.25	=1-(1/($A$5+(	0.5	=1-(1/($A$5+G10)*($A$5+G10*EXP(-($A$5+G10)*K10/$A$7)))
11	BC 1" Valve		Bubble Ch.	1	0.00000001	=D11*E11	684	=(G11/$A$5)	0.25	=1-(1/($A$5+(	0.5	=1-(1/($A$5+G11)*($A$5+G11*EXP(-($A$5+G11)*K11/$A$7)))
12	BC Valves		Bubble Ch.	2	0.00000001	=D12*E12	29	=(G12/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G12)*($A$5+G12*EXP(-($A$5+G12)*K12/$A$7)))
13	BC Bellows		Bubble Ch.	1	0.000003	=D13*E13	29	=(G13/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G13)*($A$5+G13*EXP(-($A$5+G13)*K13/$A$7)))
14	Conn. Rupture		Bubble Ch.	5	0.0000003	=D14*E14	29	=(G14/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G14)*($A$5+G14*EXP(-($A$5+G14)*K14/$A$7)))
15	Conn. Leak		Bubble Ch.	5	0.000003	=D15*E15	0.2	=(G15/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G15)*($A$5+G15*EXP(-($A$5+G15)*K15/$A$7)))
16	instruments		Bubble Ch.	1	0.00000001	=D16*E16	29	=(G16/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G16)*($A$5+G16*EXP(-($A$5+G16)*K16/$A$7)))
17	welds		Bubble Ch.	6	0.000000003	=D17*E17	29	=(G17/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G17)*($A$5+G17*EXP(-($A$5+G17)*K17/$A$7)))
18	**transfer line**		CF3I	1	0.000003	=D18*E18	17	=(G18/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G18)*($A$5+G18*EXP(-($A$5+G18)*K18/$A$7)))
19	Pipes		hydraulic	5	0.000000001	=D19*E19	10	=(G19/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G19)*($A$5+G19*EXP(-($A$5+G19)*K19/$A$7)))
20	Elbows		hydraulic	10	0.0000003	=D20*E20	10	=(G20/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G20)*($A$5+G20*EXP(-($A$5+G20)*K20/$A$7)))
21	Tees		hydraulic	4	0.0000003	=D21*E21	10	=(G21/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G21)*($A$5+G21*EXP(-($A$5+G21)*K21/$A$7)))
22	Valves		hydraulic	10	0.00000001	=D22*E22	10	=(G22/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G22)*($A$5+G22*EXP(-($A$5+G22)*K22/$A$7)))
23	Conn. Rupture		hydraulic	20	0.0000003	=D23*E23	10	=(G23/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G23)*($A$5+G23*EXP(-($A$5+G23)*K23/$A$7)))
24	Conn. Leak		hydraulic	20	0.000003	=D24*E24	0.2	=(G24/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G24)*($A$5+G24*EXP(-($A$5+G24)*K24/$A$7)))
25	Hoses Rupture		hydraulic	4	0.0000003	=D25*E25	10	=(G25/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G25)*($A$5+G25*EXP(-($A$5+G25)*K25/$A$7)))
26	Hoses Leak		hydraulic	4	0.000003	=D26*E26	0.2	=(G26/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G26)*($A$5+G26*EXP(-($A$5+G26)*K26/$A$7)))
27	instruments		hydraulic	0	0.00000001	=D27*E27	0	=(G27/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G27)*($A$5+G27*EXP(-($A$5+G27)*K27/$A$7)))
28			TOTAL									

CF3I_release_ODH table May_2010rev.xlsx

	H	I	J	K	L	M	N
1	**side Empty Water Tank**						
2							
3							
4							
5							
6							
7							
8	**Q/R**	Time	fCF3I{t1}	Time	fCF3I{t2}	**D(t2)**	**X**
9	LEAK/VENT	(t1) min.	FRACT CF3I	(t2) min.	FRACT CF3I	Exposure Factor	Exp. Rate
10	=(G10/$A$5)	0.25	=1-(1/($A$5+(	0.5	=1-(1/($A$5+G10)*($A$5+G10*EXP(-($A$5+G10)*K10/$A$7)))	=IF(L10>0.004,1,IF(L10<0.002,0,(L10-0.002)/0.0	=F10*(M10)
11	=(G11/$A$5)	0.25	=1-(1/($A$5+(	0.5	=1-(1/($A$5+G11)*($A$5+G11*EXP(-($A$5+G11)*K11/$A$7)))	=IF(L11>0.004,1,IF(L11<0.002,0,(L11-0.002)/0.0	=F11*(M11)
12	=(G12/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G12)*($A$5+G12*EXP(-($A$5+G12)*K12/$A$7)))	=IF(L12>0.004,1,IF(L12<0.002,0,(L12-0.002)/0.0	=F12*(M12)
13	=(G13/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G13)*($A$5+G13*EXP(-($A$5+G13)*K13/$A$7)))	=IF(L13>0.004,1,IF(L13<0.002,0,(L13-0.002)/0.0	=F13*(M13)
14	=(G14/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G14)*($A$5+G14*EXP(-($A$5+G14)*K14/$A$7)))	=IF(L14>0.004,1,IF(L14<0.002,0,(L14-0.002)/0.0	=F14*(M14)
15	=(G15/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G15)*($A$5+G15*EXP(-($A$5+G15)*K15/$A$7)))	=IF(L15>0.004,1,IF(L15<0.002,0,(L15-0.002)/0.0	=F15*(M15)
16	=(G16/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G16)*($A$5+G16*EXP(-($A$5+G16)*K16/$A$7)))	=IF(L16>0.004,1,IF(L16<0.002,0,(L16-0.002)/0.0	=F16*(M16)
17	=(G17/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G17)*($A$5+G17*EXP(-($A$5+G17)*K17/$A$7)))	=IF(L17>0.004,1,IF(L17<0.002,0,(L17-0.002)/0.0	=F17*(M17)
18	=(G18/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G18)*($A$5+G18*EXP(-($A$5+G18)*K18/$A$7)))	=IF(L18>0.004,1,IF(L18<0.002,0,(L18-0.002)/0.0	=F18*(M18)
19	=(G19/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G19)*($A$5+G19*EXP(-($A$5+G19)*K19/$A$7)))	=IF(L19>0.004,1,IF(L19<0.002,0,(L19-0.002)/0.0	=F19*(M19)
20	=(G20/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G20)*($A$5+G20*EXP(-($A$5+G20)*K20/$A$7)))	=IF(L20>0.004,1,IF(L20<0.002,0,(L20-0.002)/0.0	=F20*(M20)
21	=(G21/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G21)*($A$5+G21*EXP(-($A$5+G21)*K21/$A$7)))	=IF(L21>0.004,1,IF(L21<0.002,0,(L21-0.002)/0.0	=F21*(M21)
22	=(G22/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G22)*($A$5+G22*EXP(-($A$5+G22)*K22/$A$7)))	=IF(L22>0.004,1,IF(L22<0.002,0,(L22-0.002)/0.0	=F22*(M22)
23	=(G23/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G23)*($A$5+G23*EXP(-($A$5+G23)*K23/$A$7)))	=IF(L23>0.004,1,IF(L23<0.002,0,(L23-0.002)/0.0	=F23*(M23)
24	=(G24/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G24)*($A$5+G24*EXP(-($A$5+G24)*K24/$A$7)))	=IF(L24>0.004,1,IF(L24<0.002,0,(L24-0.002)/0.0	=F24*(M24)
25	=(G25/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G25)*($A$5+G25*EXP(-($A$5+G25)*K25/$A$7)))	=IF(L25>0.004,1,IF(L25<0.002,0,(L25-0.002)/0.0	=F25*(M25)
26	=(G26/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G26)*($A$5+G26*EXP(-($A$5+G26)*K26/$A$7)))	=IF(L26>0.004,1,IF(L26<0.002,0,(L26-0.002)/0.0	=F26*(M26)
27	=(G27/$A$5)	0.5	=1-(1/($A$5+(	1	=1-(1/($A$5+G27)*($A$5+G27*EXP(-($A$5+G27)*K27/$A$7)))	=IF(L27>0.004,1,IF(L27<0.002,0,(L27-0.002)/0.0	=F27*(M27)
28							**=SUM(N10:N27)**

[i] Skaggs, S. R., and Rubenstein, R., "Setting the Occupational Exposure Limits for CF3I," Proceedings, Halon Options Technical Working Conference, Albuquerque, NM, pp. 254-261, 1991.
[ii] Fermi National Accelerator Lab ES&H Manual chapter 5064, May 2009 revision, http://www-esh.fnal.gov/FESHM/5000/5064.htm.
[iii] National Research Council, Committee on Toxicology, Subcommittee on Iodotrifluoromethane, "Iodotrifluoromethane: Toxicity Review". (National Academies Press, 2004), p. 3.