ODH, Oxygen Deficiency Hazard Cryogenic Analysis

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ODH, OXYGEN DEFICIENCY HAZARD CRYOGENIC ANALYSIS

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ABSTRACT

An oxygen deficiency exists when the concentration of oxygen, by volume, drops to a level at which atmosphere supplying respiratory protection must be provided. Since liquid cryogens can expand by factors of 700 (LN₂) to 850 (LHe), the uncontrolled release into an enclosed space can easily cause an oxygen-deficient condition. An oxygen deficiency hazard (ODH) fatality rate per hour (Φ) is defined as: $\Phi = \sum N_i P_i F_i$, where N_i = number of components, P_i = probability of failure or operator error, and F_i = fatality factor. ODHs range from "unclassified" ($\Phi < 10^{-9}$ 1/h) to class 4, which is the most hazardous ($\Phi > 10^{-1}$ 1/h). For Superconducting Super Collider Laboratory (SSCL) buildings where cryogenic systems exist, failure rate, fatality factor, reduced oxygen ratio, and fresh air circulation are examined.

INTRODUCTION

An oxygen deficiency exists when the concentration of oxygen by volume drops to a level at which atmosphere supplying respiratory protection must be provided. This condition is defined in the "SSCL Oxygen Deficiency Hazards Procedure" to exist when the atmospheric oxygen concentration is less than 19.5 %. Since liquid cryogen can expand to room temperature by a factor from 700 (LN₂) to 850 (LHe), uncontrolled release into an enclosed space can easily cause an oxygen-deficient condition. The ODH classes with relation to the fatality rate F are presented in Table 1.

In order to quantify the degree of hazard associated with an accidental release of cryogen, an ODH fatality rate per hour is defined as:

$$\Phi = \sum N_i P_i F_i, \quad (1)$$

where N_i = number of i-type component

P_i = probability that the i-th component failure or operator error will occur [1/h]

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F_i = fatality factor; it is the probability that occurrence of the i-th failure will result in a fatality [fatalities per failure].

Table 1. ODH Classes.

ODH Class	Fatality Rate Φ 1/h
Unclassified	$F < 1.0 \cdot 10^{-9}$
0	$1.0 \cdot 10^{-9} \leq F < 1.0 \cdot 10^{-7}$
1	$1.0 \cdot 10^{-7} \leq F < 1.0 \cdot 10^{-5}$
2	$1.0 \cdot 10^{-5} \leq F < 1.0 \cdot 10^{-3}$
3	$1.0 \cdot 10^{-3} \leq F < 1.0 \cdot 10^{-1}$
4	$F \geq 1.0 \cdot 10^{-1}$

CALCULATION

Failure Rates

The failure rates used are based on Fermi National Accelerator Laboratory (FNAL) experience with the Tevatron,^{1,2} manufacturer experience with specific components, and data from the Nuclear Regulatory Commission (NRC).³ Use of FNAL statistics is justified by noting that the failure rates are for industry-standard components and are based on data gathered during start-up of the Tevatron. Use of NRC statistics is justified by noting that they were gathered from a variety of sources, including various industrial plants, many of which were designed and built to the same codes as the cryogenic plant. Additional calculations are based on the British Cryogenic Counsel manual,⁴ and Superconducting Super Collider Laboratory experience.^{5,6,7}

Fatality Factors

The fatality factor F is defined for different oxygen concentrations fO_2 as follows:

$$\begin{aligned} \text{for } fO_2 \leq 0.088, & \quad F = 1.00E+00; \\ \text{for } fO_2 \geq 0.180, & \quad F = 1.00E-07. \end{aligned}$$

The fatality factor varies continuously as the function of fO_2 , over the range:

$$0.088 \leq fO_2 \leq 0.180.$$

All exposures with $fO_2 \geq 0.18$ are safe and do not contribute to fatality. The lower level $fO_2 \leq 0.088$ is the oxygen concentration providing one minute of useful consciousness. Between these limits, the fatality factor can be given by an exponential function:

$$F = \text{EXP}(a + b \cdot p \cdot fO_2), \quad (2)$$

where p = atmospheric pressure [Torr]
 fO_2 = fraction of oxygen.

For specific elevations above sea level the atmospheric pressure can be determined as:

$$p_{\text{aver}} = p_0 \cdot (1 - 0.0065 \cdot A/T_0), \quad (3)$$

where A = elevation above sea level [m]
 $T_0 = 288.16$ [K]
 $p_0 = 101.33$ [kPa].

To an acceptable level of accuracy the fatality factor can be expressed as the following exponential function of oxygen fraction:

$$F = \text{EXP}(15.417 - 175.197 \cdot f_{O_2}), \quad (4)$$

when $F = 1$ at $\{f_{O_2} = 0.088\}$, and $F = 1.00E-07$ at $\{f_{O_2} = 0.180\}$.

Oxygen Concentration

The reduced fraction of oxygen f_{O_2} as a function of time must be known to calculate the fatality factor F . In order to approximate the change of f_{O_2} resulting from a cryogen leak into a volume V , the following assumption are made:

1. complete and rapid mixing of all gasses occurs throughout the entire volume
2. the ventilation and leak rates can be approximated as constant
3. the atmospheric pressure in the building remains constant
4. the fresh air supplied to the building contains 21% oxygen

During the leak the oxygen concentration is given by:

$$f_{O_2}(t_r) = C_r(t_r) = \{0.21/(Q+R)\} \{Q+R \cdot e^{-[(Q+R)(t/V)]}\}. \quad (5)$$

After the leak has ended the oxygen concentration is given by:

$$f_{O_2}(t_e) = C_e(t_e) = 0.21[1 - e^{(-Q \cdot t/V)}] + C_r(t_r) \cdot e^{(-Q \cdot t/V)}, \quad (6)$$

where V = building volume [m^3]
 t = time from the start of the leak release [s]
 R = liquid or gas leak rate as equivalent @ 300K and 1Bar [m^3/s]
 Q = fresh air circulation rate [m^3/s].

The lowest attainable fraction of oxygen for a given leak rate occurs at $t=\infty$, and is given by:

$$f_{O_2}(t=\infty) = 0.21 \{Q/(Q+R)\}. \quad (7)$$

When a fixed volume leak is postulated, like emptying a LHe or LN₂ dewar, the fraction of oxygen can be approximated by:

$$f_{O_2}(t=\infty) = 0.21 \{(V - V_{\text{gas}})/V\}, \quad (8)$$

where V_{gas} = total volumes of liquid or gas leak as equivalent @ (300 K and 1Bar) [m^3].

General Comments

Cryogenic systems are divided into subsystems, most of which are vacuum insulated. A large internal leak to an insulating vacuum volume will eventually find its way to room air through a relief valve. A worst-case leak rate for an internal component is taken to be equal to the maximum design flow rate for that component.

Failure of cryogenic piping and weld joints can lead to an ODH situation. The total length of pipe is estimated as an average length between major discontinuities (valves, pumps, etc.). To estimate the number of welds, it is assumed that each piece of pipe, each valve, and each reduction joint involves two welds. The total is multiplied by a safety factor of 1.5 to obtain an estimate of the number of internal welds. Since the relevant failure rates

for lengths of pipe and welds are of order $1.0 \times 10^{-9}/h$, a factor of 2 or 3 in these estimates is seldom crucial. Finally, the worst-case leak rates for either a pipe or a weld failure are taken to be the average maximum flow rate within the appropriate subsystem.

There are a limited number of paths, however, that lead directly to the atmosphere. A subsystem can leak directly to room air through connective piping, valve stems, pressure tap seals, bayonets, etc. In the case of pipe failure, worst-case leak rates are taken to be equal to the maximum design flow rate. In the case of valves, pressure taps, and bayonets, an estimate of the maximum flow achievable is used as the worst-case leak rate. The maximum flow is estimated using worst-case pressure differentials.

The failure rate of a cryogenic fluid line that contains bayonets is estimated to be $3.0 \times 10^{-6}/h$. The NRC failure rates indicate a failure rate of $3.0 \times 10^{-6}/h$ for gaskets and $3.0 \times 10^{-7}/h$ for other types of closures. Since a bayonet seal uses a rubber O-ring and V-band, an approximation is made by assuming that a cryogenic fluid line contains two bayonets. Thus, the failure rate of a single bayonet is taken to be $1.5 \times 10^{-6}/h$. One additional failure mode associated with bayonets is due to improper installation (operator error). The estimated probability of a large cryogen spill resulting from a U-tube change, calculated by demand, is 1.0×10^{-3} . Estimating the demand rate to be on the order of $5.0 \times 10^{-2}/h$, a failure rate is $5.0 \times 10^{-5}/h$.

In all cases, leaking cryogen's are assumed to warm to 300K and 1Bar immediately upon release to the atmosphere. Thus, the leak rate is given by the mass flow rate divided by the appropriate 300 K and 1Bar gas density.

EXAMPLE OF ANALYSIS

A sample set of calculations is presented for a building containing helium compressors with oil skid, helium refrigerator and liquefier, helium distribution box, helium storage tanks, and penetration and connecting pipes.

Basic calculation data are as below. The volume of the building is 2450 m^3 (with 10% less for the volume of the equipment), elevation above sea level is 200 m, and atmospheric pressure is 98.92kPa (742 Torr). To determine the fatality factor between $f_{O_2} = 0.088$ and $f_{O_2} = 0.18$, the resulting equation is:

$$F = \text{EXP}(15.417 - 175.197 \cdot f_{O_2}). \quad (9)$$

The flow is determined as the maximum liquid or gas cryogen flow from the process data line schedule for a specific subsystem. The failure rate is the value for a specific component and a component failure rate is the value of specific element failure rates multiplied by the numbers of these elements. The leak rate R of cryogen flow is calculated in m^3/s at room temperature and pressure. The leak ratio is the fresh air circulation (Q) divided by the sum of fresh air circulation (Q) and cryogen leak rate (R). Reduced oxygen ratio is calculated as 0.21 of leak ratio. The fatality rate is the product of component's failure number multiplied by fatality factor.

RESULTS

Results of the calculation, for the minimum fresh air circulation $Q = 0.621 \text{ m}^3/\text{s}$, are presented in Table 2.

The total fatality rate as a function of the fresh air supply for this case is shown in Figure 1. The minimum ventilation rate consistent with class 0 is $0.621 \text{ m}^3/\text{s}$. It is evident from Figure 1 that the fatality rate, with the ventilation system off, is about $1.0 \times 10^{-4}/h$. This implies that the supplies and returns fan system of ventilation units must have a probability of failure no greater than $1.0 \times 10^{-3}/h$, so that the probability of a leak occurring while HVAC is in some failed state is also less than $1.0 \times 10^{-7}/h$. In the case of an on-demand ventilation scheme, the probability that the system fails to come on and run must also be no greater than $1.0 \times 10^{-4}/h$.

Table 2. Fatality rate calculation for fresh air circulation $Q = 0.621 \text{ m}^3/\text{s}$

System Subsystem Components	N Component Num.	Flow	P Failure Rate	Components Failure Rate	R Leak Rate	Q/(Q+R) Leak Ratio	F _{O2} [∞] Reduced Oxygen Ratio	F(aver) Fatality Factor	Ø Fatality Rate
		g/s	/h	n*P	m3/s				
Compressor and oil skid									
Compressor	1	72	1.00E-05	1.00E-05	0.44	0.58	0.12	2.28E-03	2.28E-08
Oil separator	1	72	1.00E-06	1.00E-06	0.44	0.58	0.12	2.28E-03	2.28E-09
Oil cooler	2	72	1.00E-06	2.00E-06	0.44	0.58	0.12	2.28E-03	4.57E-09
Oil absorber	2	72	1.00E-06	2.00E-06	0.44	0.58	0.12	2.28E-03	4.57E-09
Oil heater	1	72	1.00E-06	1.00E-06	0.44	0.58	0.12	2.28E-03	2.28E-09
Piping internal	15	72	1.00E-09	1.50E-08	0.44	0.58	0.12	2.28E-03	3.43E-11
Valves	10	72	1.00E-08	1.00E-07	0.44	0.58	0.12	2.28E-03	2.28E-10
Welds	30	72	3.00E-09	9.00E-08	0.44	0.58	0.12	2.28E-03	2.06E-10
Tank dryer	1	72	1.00E-06	1.00E-06	0.44	0.58	0.12	2.28E-03	2.28E-09
Welds	10	72	3.00E-09	3.00E-08	0.44	0.58	0.12	2.28E-03	6.85E-11
Refrigerator and Liquefier									
Internal									
Vacuum vessel of refrigerator	1	72	1.00E-06	1.00E-06	0.44	0.58	0.12	2.28E-03	2.28E-09
Heat exchanger	6	72	1.00E-06	6.00E-06	0.44	0.58	0.12	2.28E-03	1.37E-08
Adsorber	3	72	1.00E-06	3.00E-06	0.44	0.58	0.12	2.28E-03	6.85E-09
Surge vessel	2	72	1.00E-06	2.00E-06	0.44	0.58	0.12	2.28E-03	4.57E-09
Expander	2	20	3.00E-06	6.00E-06	0.12	0.84	0.18	2.26E-07	1.35E-12
Piping internal	15	50	1.00E-09	1.50E-08	0.31	0.67	0.14	1.00E-04	1.50E-12
Welds	255	72	3.00E-09	7.65E-07	0.44	0.58	0.12	2.28E-03	1.75E-09
Filter	5	72	1.00E-06	5.00E-06	0.44	0.58	0.12	2.28E-03	1.14E-08
External									
Valves	50	72	1.00E-08	5.00E-07	0.44	0.58	0.12	2.28E-03	1.14E-09
Welds	75	72	3.00E-09	2.25E-07	0.44	0.58	0.12	2.28E-03	5.14E-10
Pressure tabs	10	30	3.00E-07	3.00E-06	0.18	0.77	0.16	2.35E-06	7.04E-12
Bayonets	4	72	1.50E-06	6.00E-06	0.44	0.58	0.12	2.28E-03	1.37E-08
Cold box									
Internal									
Vacuum vessel	1	50	1.00E-06	1.00E-06	0.31	0.67	0.14	1.00E-04	1.00E-10
Cooler	2	50	1.00E-06	2.00E-06	0.31	0.67	0.14	1.00E-04	2.00E-10
Cold pump	1	50	5.00E-06	5.00E-06	0.31	0.67	0.14	1.00E-04	5.00E-10
Piping internal	15	50	1.00E-09	1.50E-08	0.31	0.67	0.14	1.00E-04	1.50E-12
Welds	150	50	3.00E-09	4.50E-07	0.31	0.67	0.14	1.00E-04	4.50E-11
External									
Valves	30	50	1.00E-08	3.00E-07	0.31	0.67	0.14	1.00E-04	3.00E-11
Welds	100	50	3.00E-09	3.00E-07	0.31	0.67	0.14	1.00E-04	3.00E-11
Pressure tabs	10	30	3.00E-07	3.00E-06	0.18	0.77	0.16	2.35E-06	7.04E-12
Bayonets	6	50	1.50E-06	9.00E-06	0.31	0.67	0.14	1.00E-04	9.01E-10
GHe storage tank, 68000L@300K and 18Bar									
Tank	1	5	1.00E-06	1.00E-06	0.03	0.95	0.20	0.00E+00	0.00E+00
Valves	5	5	1.00E-08	5.00E-08	0.03	0.95	0.20	0.00E+00	0.00E+00
Welds	20	5	3.00E-09	6.00E-08	0.03	0.95	0.20	0.00E+00	0.00E+00
Catastrophic leaks (calc.per g/s)	1	816	1.00E-09	1.00E-09	5.01	0.11	0.02	1.00E+00	1.00E-09
GHe storage tank,

Figure 1. Total fatality rate as the function of fresh air circulation.

Figure 2. Oxygen concentration as a function of cryogen leak.

The correlation between oxygen building concentration and real leak time, with assumptions described above, is shown in Fig 2. In this case, ventilation system power is off, and there is no fresh air supply to the building ($Q=0 \text{ m}^3/\text{s}$). During the leak, helium gas is concentrated in the upper part of the building, filling one third of the total building volume ($V/3=817\text{m}^3$). Leak rates from 100 g/s to 1000 g/s are included. This figure shows that in the worst catastrophic situation (helium broken line supplies 1000 g/s of gas), there is about 100 s to clear the building of personnel.

CONCLUSION

A method for determining the fatality rate during leak of cryogen was discussed. The method was demonstrated by applying it to a building with cryogenic equipment. An estimate of the time to evacuate the building was made for a catastrophic evaluation.

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