Fermilab

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Memorandum

May 7, 2009

To: Bruce Chrisman

From: Nancy Grossman

Subject: Revised FESHM Chapter 5064 – Oxygen Deficiency Hazards (ODH)

FESHM chapter 5064, Oxygen Deficiency Hazard (ODH) has been revised. Both significant and minor modifications have been reviewed and approved by Cryogenic Safety Subcommittee. The changes are summarized below.

1. Change of scope to address areas with an oxygen concentration between 18% and 19.5% and reconcile FESHM 5064 with OSHA (19.5%) requirements
2. Invocation of the ALARA principal to safety measures dealing with oxygen deficiency hazards
3. Rewording and augmentation of definitions.
4. Addition to Division/Section Head responsibilities regarding maintenance of records.
5. Modifications to require that all areas be engineered so they are ODH class 2 or lower during normal operations. ODH classes 3 and 4 are eliminated. (To date, no areas at Fermilab intended for human entry during normal operations have been assigned ODH Class 3 or 4). A Director's exception is required if an area cannot be engineered to meet the requirements of ODH Class 2 or lower.
6. Addition of wording so that procedures already described in the ODH safety training booklet are required by FESHM 5064
7. Addition of wording to address entry into areas with unusual oxygen deficiency hazards
8. Addition of wording to address underground installations with oxygen deficiency hazards.
9. Rewording of the introductory paragraph to 5064TA to include the ALARA principle
10. Clarification specifying that ODH classifications are based upon the most severe oxygen deficiency hazard: a fatality. Boundaries between ODH classes 0, 1, and 2 remain unchanged; as a result, existing ODH analyses and classifications of various areas remain valid.
11. Reformatting so that the equations of 5064TA are more legible
12. Elimination of ODH Classes 3 and 4 from the Oxygen Deficiency Hazard Table

13. Simplifications to the table "ODH Control Measures" and associated text to take into account the elimination of ODH classes 3 and 4
14. Elimination of examples of signs for former classifications ODH 3 and ODH 4
15. Minor changes to grammar and spelling throughout FESM 5064

This chapter was out for labwide review and all comments were addressed.

After final approval, please return this approval page to Elizabeth Bancroft at MS119 for posting on the web.

Encl.

Recommended for Approval:

Bruce Chrisman Date 5/12/09

Approved:

Piermaria Oddone Date 5/12/09

OXYGEN DEFICIENCY HAZARDS (ODH)

INTRODUCTION

The use of compressed and liquefied gases is commonplace at Fermilab. The introduction of these materials to the atmosphere can present a hazard. In particular, persons exposed to reduced-oxygen atmospheres may experience reduced abilities, unconsciousness, or death. The purpose of this chapter is to specify requirements for assessing the potential for and controlling hazards associated with a possible oxygen deficient environment. This chapter does not address the general topic of confined spaces (see Chapter 5063 and definition of "ODH operation" below).

APPLICABLE STANDARDS

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

DEFINITIONS

ALARA (As Low As Reasonably Achievable) - The approach to protection from hazards by managing and controlling exposure to potential hazards (both individual and collective) to the work force and to the general public at levels as low as is reasonable, taking into account social, technical, economic, practical and public policy considerations. As used in this Manual, ALARA is not a hazard limit but a process which has the objective of reducing hazards as far below the applicable limits as is reasonably achievable.

mmHg - a unit of measure of pressure based upon a liquid mercury column. The pressure exerted by gravity at the base of a liquid mercury column n mm tall is n mmHg.

ODH Monitor - a device, usually permanently attached to a structure, which monitors the concentration of oxygen and alarms at a set value. ODH monitors must alarm at 18% oxygen or higher and can be used to activate other systems.

Operations - activities, which are performed in a specific area or location. Operations include simply being in a specific location.

Oxygen concentration - the molar fraction of a gaseous mixture represented by oxygen. For a mixture of ideal gases, it is also equal to the ratio of the partial pressure of oxygen to the total mixture pressure. The oxygen concentration in normal ambient atmosphere is 20.9% (~21%).

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Oxygen deficiency - any condition under which the partial pressure of atmospheric oxygen is less than 144 mmHg (about 19.5% by volume at a barometric pressure of 740 mmHg at Fermilab).

Oxygen deficient area - any area known to have an oxygen deficiency.

Oxygen deficiency hazard (ODH) operation - an operation which exposes personnel to an increased risk of fatality in excess of 10^{-7}/hr due to oxygen deficiency. Unlike confined spaces, ODH work spaces are generally designed for occupancy and provided with normal building-type access and egress. In addition, the hazard is primarily limited to oxygen deficiency which is well understood and controlled through quantitative risk assessment.

Partial pressure - the pressure due to one of several components of a gaseous mixture. For a mixture of ideal gases, the sum of component partial pressures equals the mixture pressure.

Personal Oxygen Monitor - a device carried by an individual that monitors the concentration of oxygen and alarms at a set value. All personal Oxygen Monitors used at Fermilab are set to alarm at the mandatory confined space limit of 19.5% (see Chapter 5063).

SCBA (Self-Contained Breathing Apparatus) - a device worn by rescue workers, firefighters, and others to provide breathable air in a hostile environment. An SCBA typically has three main components: a high-pressure tank (*e.g.*, 2200 psi to 4500 psi), a pressure regulator, and an inhalation connection (mouthpiece, mouth mask or face mask), connected together and mounted to a carrying frame.

Self-Rescue supplied atmosphere respirator (escape pack) - a device containing breathing air to be used for escape during an ODH event. Such a device normally provides an air supply which lasts approximately five minutes and is to be used for escape only.

SPECIAL RESPONSIBILITIES

Division/Section heads or their designees have the responsibility of implementing the requirements of this chapter. This includes appointment of qualified persons to review, approve, and maintain documentation for ODH risk assessments under the control of their organizations; maintain records of reliability of ODH-associated equipment; and maintain records of incidents which have resulted in an oxygen deficient atmosphere.

The ES&H Section has the responsibility for the purchase and maintenance of personal oxygen monitors and the provision of standardized warning signs as described in the Technical Appendix to this document. In addition, the Medical Department is responsible for reviewing the medical fitness of persons who participate in ODH operations.

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The Cryogenic Safety Subcommittee and/or the Mechanical Safety Subcommittee serve division/section heads and the ES&H Section in a consulting capacity on ODH risk assessment issues.

The Industrial Hygiene Subcommittee provides oversight and consulting on the technologies and procedures for monitoring oxygen deficient atmospheres.

PROCEDURES

1. A quantitative assessment of the increased risk of fatality from exposure to reduced atmospheric oxygen shall be conducted for all operations, which are physically capable of exposing individuals to an oxygen deficiency. This assessment shall assign an Oxygen Deficiency Hazard Class to each area with potential risk as well as specify any unusual precautionary requirements. The classification of an area can change depending on the operations being performed. If conditions and/or activities change in ways that significantly increase the risk, the associated quantitative assessment must be accordingly revised. The technical appendix entitled "ODH Risk Assessment" is to be used in carrying out the assessment.

2. Control measures appropriate to the ODH Class shall be implemented as stated in the risk assessment and Technical Appendix. ODH Class 0 is the least hazardous. ODH Class 2 is the most hazardous. The technical appendix entitled "ODH Control Measures" is to be followed to control the potential ODH hazard.

3. Equipment at Fermilab shall be designed and installed (engineered) to ensure that areas intended for human entry during normal operation will be ODH Class 0, ODH Class 1, or ODH Class 2. No area intended for human entry during normal operation will be engineered for an ODH Class higher than 2. For Confined Space requirements (not under the scope of this chapter), see Chapter 5063.

   3.1. If an area cannot be engineered to satisfy requirements leading to an ODH Class of 2 or lower, the Division/Section Head responsible for the area must submit a written exception request to the Director or Director's designee. The request should include a justification and an evaluation of hazards, procedures, and safety measures. The request must be approved by the Director or designee before operations contributing to oxygen deficiency hazards are begun.

4. The ALARA principle shall be applied. Occupancy of areas with oxygen deficiency hazards should be limited to the extent practical while still allowing work to be performed expeditiously. Work in such areas should be planned to minimize the duration of occupancy. Offices should not normally be located in areas with oxygen deficiency hazards.

5. Divisions/Sections should maintain records of reliability of ODH-associated equipment and records of ODH alarms that were the result of an oxygen deficient

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atmosphere. These data should be periodically reviewed by the Cryogenic Safety Subcommittee to improve failure rate estimates such as those included in the Technical Appendix to this chapter.

6. Response to an alarm from a personal oxygen monitor:

   6.1. If one person is working alone in an area and his/her personal oxygen monitor alarms, the person must immediately don a self-rescue supplied atmosphere respirator (escape pack), evacuate the area, and dial 3131 to report an emergency.

   6.2. If two or more people are working together in an area and a personal oxygen monitor alarms, they should compare readings. If other monitors read OK, then everyone must evacuate the area and solve the problem with the personal oxygen monitor before re-entering. If other monitors confirm low oxygen levels, then everyone must don an escape pack, evacuate the area, and then dial 3131 to report an emergency.

7. Response to an alarm from an in-place oxygen monitor:

   7.1. If one person is working alone in an area and an in-place oxygen monitor alarms, and his/her personal oxygen monitor reads greater than 19.5%, the person should evacuate the area going away from the assumed source of the alarm. After exiting, he/she should notify the operations department responsible for the area of the problem. He/she should not re-enter until the problem has been solved. If a personal oxygen monitor has alarmed as well, the procedure of 6.1 should be followed.

   7.2. If two or more people are working together, they should compare readings of personal oxygen monitors. If all personal oxygen monitors read OK, everyone should evacuate the area going away from the assumed source of the alarm. After evacuating, they should notify the operations department responsible for the area of the problem. They should not re-enter the area until the problem has been solved. If a personal oxygen monitor confirms low oxygen levels, everyone should don an escape pack, evacuate the area, and then dial 3131 to report an emergency.

8. Response to other indications of a possible cryogen or gas leak (vapor cloud, sound of gas leak, etc.):

   8.1. If one person is working alone and his/her personal oxygen monitor reads greater than 19.5%, he/she should evacuate the area going away from the assumed source of the problem. After exiting, he/she should notify the operations department responsible for the area of the problem. If a personal oxygen monitor has alarmed, he/she must immediately don a self-rescue

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supplied atmosphere respirator (escape pack), evacuate the area, and dial 3131 to report an emergency.

8.2. If two or more people are working together, they should compare personal oxygen monitor readings. If all are OK, they should all evacuate the area going away from the assumed source of the problem. After exiting, they should notify the operations department responsible for the area of the problem. If a personal oxygen monitor has alarmed, they must immediately don self-rescue supplied atmosphere respirators (escape packs), evacuate the area, and dial 3131 to report an emergency.

9. Entry into an area with unusual oxygen deficiency hazards:

9.1. Any rescue must be conducted by emergency (Fire Department) personnel. If an area is suspected to be oxygen deficient or to present unusual oxygen deficiency hazards, an unexposed observer and the use of SCBA equipment are required. Training and medical approval are required for the use of SCBA equipment.

9.2. If, for purposes other than rescue, entry must be made into an oxygen deficient area or an area suspected to present unusual oxygen deficiency hazards, the Division/Section Head responsible for the area must submit a written request to the Director or Director's designee which includes a justification and outlines hazards, procedures, and safety measures. The request must be approved by the Director or designee before entry.

10. In general, ODH evaluation procedures and measures to address hazards in underground installations are the same as those required for surface installations. However, time of egress may be longer, inerting gases or cryogenic fluids may accumulate, and rescue operations may be more difficult. All of these factors must be taken into account in analyses and protective measures.

10.1. If there are oxygen deficiency hazards and normal entry and egress is by means other than by foot, at least one egress path to a "safe area" which can be reached by foot must be provided. The safe area must be free of oxygen deficiency hazards and remain so during all plausible equipment failures. If the safe area relies upon ventilation, emergency power must be provided to its ventilation systems.

10.2. The path to the safe area must be adequately marked and illuminated and remain free of obstructions during plausible ODH incidents.

10.3. A written plan for evacuation of personnel from the safe area to the surface must be prepared and approved.

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TECHNICAL APPENDIX

1. ODH RISK ASSESSMENT

The ALARA principle is to be applied to all areas with oxygen deficiency hazards. Any area known to have an oxygen concentration <19.5% is considered to be an oxygen deficient area. All areas intended for human occupancy at Fermilab shall have an environment or environmental controls which will normally ensure that the concentration of oxygen remains above19.5%. If an area contains equipment or sources of inert gas which could lead to a significant decrease in oxygen concentration, additional measures shall be taken to reduce risk to personnel. The goals of an ODH risk assessment are to evaluate the level of risk in a given area, to classify the area based upon the level of risk, that is, to assign an ODH Class to the area, and to specify additional safety measures to be taken to reduce risks. The ODH risk assessment should be documented, reviewed, and approved.

The ODH Class is based upon the most severe risk: the likelihood that a fatality will occur. Since the level of risk is tied to the area and the nature of the operation, the fatality rate shall be determined on an operation-by-operation basis. For a given area and operation several events may cause an oxygen deficiency. Each event has an expected rate of occurrence and each occurrence has an expected probability of causing a fatality. The oxygen deficiency hazard fatality rate is defined as:

$$\phi = \sum_{i=1}^{n} P_i F_i$$

where ϕ = the ODH fatality rate (per hour),

P_i = the expected rate of the ith 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. When possible, the value of P_i shall be determined by operating experience at Fermilab; otherwise data from similar systems elsewhere or other relevant values shall be used. Estimates of equipment failure rates are given in Table 1 and Table 2. Table 1 contains median estimates collected from past ODH risk assessments at Fermilab (see appendix 1). Table 2 contains values derived from the nuclear power industry. General human error rate estimates are presented in Table 3.

The risk assessment should also consider the benefit of existing active control systems such as forced ventilation or any supply shut-off valves which are automatically activated by area monitor readings or system failure indicators. These systems must be designed to be activated before the area drops below 18% oxygen concentration. Although such systems or any forced ventilation system reduces overall risk, they are

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also subject to failure and this shall be factored into the risk assessment. This is accomplished by summing the expected failure rate of all systems and the corresponding fatality factors for when those systems have failed. For example, a fan which is triggered by a low oxygen monitor reading may not function properly because of a power failure, inadequate maintenance, or the monitor's calibration drifting. Therefore, the probability that these failures will occur and compromise the ventilation system shall be factored into the overall risk assessment. Also, since the ϕ calculation for defining ODH hazard is based on untrained personnel using no special personal protection, the risk assessment must assume that personnel take no direct action in responding to ODH conditions. For example, ϕ cannot be reduced by assuming a person hearing an alarm will exit.

The value of F_i is the probability that a person will die if the ith event occurs. The value depends on the oxygen concentration. For convenience of calculation, an approximate relationship between the value of F_i and the lowest attainable oxygen concentration has been developed (Figure 1). The lowest attainable concentration is used, rather than an average, since that minimum value is conservative and the time dependence of the concentration is normally not well known. 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 ϕ 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.

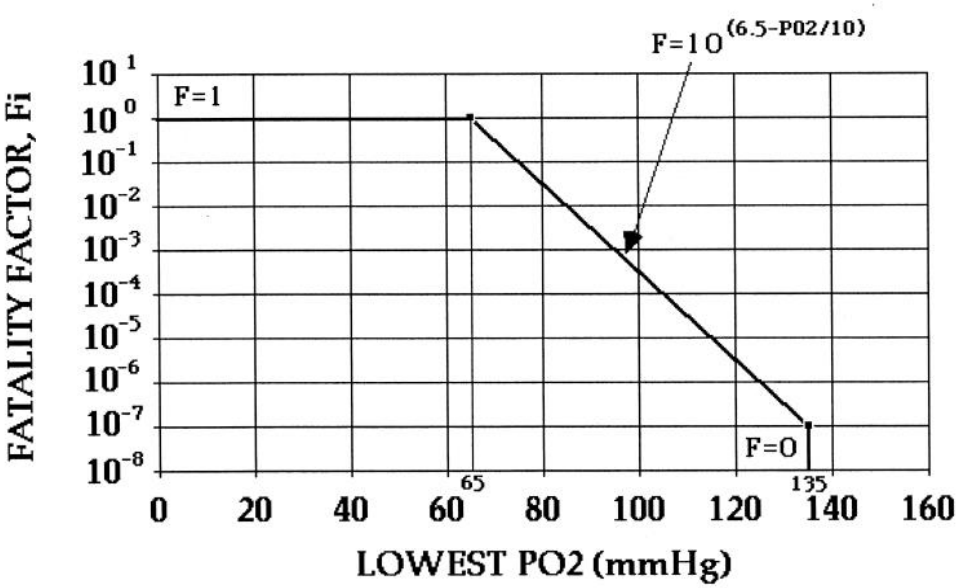

Figure 1 - Graph of the logarithm of the fatality factor (F_i) versus the lowest attainable oxygen concentration which can result from a given event. This relationship should be used when no better estimate of the probability of fatality from a given event is

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available.

Table 1

Fermilab Equipment Failure Rate Estimates

System	Failure Mode	Failure Rate
Compressor (Two-stage Mycom)	Leak Component rupture	5×10^{-6}/hr 3×10^{-7}/hr
Dewar	Loss of vacuum	1×10^{-6}/hr
Electrical Power Failure (unplanned)	Time Rate Demand Rate Time Off	1×10^{-4}/hr 3×10^{-4}/D 1 hr
Fluid Line (Cryogenic)	Leak Rupture	5×10^{-7}/hr 2×10^{-8}/hr
Cryogenic Magnet (Powered, unmanned)	Rupture	2×10^{-7}/hr
Cryogenic Magnet (Not powered, manned)	Rupture	2×10^{-8}/hr
Header Piping Assembly	Rupture	1×10^{-8}/hr
U-Tube Change (Cryogen Release)	Small Event Large Event	3×10^{-2}/D 1×10^{-3}/D

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Table 2

NRC Equipment Failure Rate Estimates

(An alternative reference source which is generally in good agreement with these NRC equipment failure rates is "Guidelines for Process Equipment Reliability Data by the Center for Chemical Process Safety of AIChE".)

	Failure Mode	Median Failure Rate
BATTERIES, POWER (UPC) SUPPLIES	No output	3x10-6/HR
CIRCUIT BREAKERS	Failure to Operate	1x10-3/D
	Premature Transfer	1x10-6/HR
DIESEL		
(Complete Plant)	Failure to Start on Demand	3x10-2/D
(Emergency Run Loads)	Failure to Run	3x10-3/HR
(Engine Only)	Failure to Run	3x10-4/HR
ELECTRIC MOTORS	Failure to Start	3x10-4/D
	Failure to Run – Normal Envir.	1x10-5/HR
	Failure to Run - Extreme Envir.	1x10-3/HR
FUSES	Premature, Open	1x10-6/HR
	Failure to Open	1x10-5/D
GASKETS Flanges, Closures, Elbows	Leak	3x10-6/HR
	Leak/Rupture	3x10-7/HR
INSTRUMENTATION	Failure to Operate	1x10-6/HR
	Shifts	3x10-5/HR
(Amplification Annuciators, Transducers, Calibration, Combination)		

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PIPES >3" Hi Quality	Rupture (Section)	1x10-10/HR
PIPES <3"	Rupture	1x10-9/HR
PUMPS	Failure to Start	1x10-3/D
	Failure to Run – Normal	3x10-5/HR
	Failure to Run - Extreme Env.	1x10-3/HR
RELAYS	Failure to Energize	1x10-4/D
	Failure NO Contact to Close	3x10-7/HR
	Short Across NO/MC Contact	1x10-8/HR
	Open NC Contact	1x10-7/HR
SOLID STATE DEVICES		
HI PWR application	Fails to Function	3x10-6/HR
	Shorts	1x10-6/HR
Low PWR application	Fails to Function	1x10-6/HR
	Shorts	1x10-7/HR
SWITCHES	Limit: Failure to Operate	3x10-4/D
	Torque: Fail to OPER	1x10-4/D
	Pressure Fail to OPER	1X10-4/D
	Manual, Fail to TRANS	1x10-5/D
	Contacts Shorts	1x10-8/HR
TRANSFORMERS	Open CKT	1x10-6/HR
	SHORT	1x10-6/HR
VALVES (MOV)	Fails to Operate (Plug)	1x10-3/D
	Failure to Remain Open	1x10-4/D
	External Leak or Rupture	1x10-8/HR
VALVES (SOV)	Fails to Operate	1x10-3/D
VALVES (AOV)	Fails to Operate (Plug)	3x10-4/D
	Failure to Remain Open	1x10-4/D
	External Leak-Rupture	1x10-8/HR
VALVES (Check)	Failure to Open	1x10-4/D
	Reverse Leak	3x10-7/HR
	External Leak-Rupture	1x10-8/HR
VALVES (Vacuum)	Failure to Operate	3x10-5/D
	Rupture	1x10-8/HR

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VALVES: Orifices, Flow Meters, (Test)	Rupture	1x10-8/HR
VALVES (Manual)	Failure to Remain Open (Plug)	1x10-4/D
VALVES (Relief)	Fail to Open/D Premature Open/HR	1x10-5/D 1x10-5/HR
WELDS	Leak	3x10-9/HR
WIRES	Open Short to GND Short to PWR	3x10-6/HR 3x10-7/HR 1x10-8/HR

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Table 3

Human Error Rate Estimates

Est Error Rate (D^{-1})	Activity
10^{-3}	Selection of a switch (or pair of switches) dissimilar in shape or location to the desired switch (or pair of switches), assuming no decision error. For example, operator actuates large handled switch rather than small switch.
3×10^{-3}	General human error of commission, e.g., misreading label and therefore selecting wrong switch.
10^{-2}	General human error of omission where there is no display in the control room of the status of the item omitted, e.g., failure to return manually operated test valve to proper configuration after maintenance.
3×10^{-3}	Errors of omission, where the items being omitted are embedded in a procedure rather than at the end as above.
$1/x$	Given that an operator is reaching for an incorrect switch (or pair of switches), he selects a particular similar appearing switch (or pair of switches), where x = the number of incorrect switches (or pair of switches) adjacent to the desired switch (or pair of switches). The $1/x$ applies up to 5 or 6 items. After that point the error rate would be lower because the operator would take more time to search. With up to 5 or 6 items he doesn't expect to be wrong and therefore is more likely to do less deliberate searching.
10^{-1}	Monitor or inspector fails to recognize initial error by operator. Note: With continuing feedback of the error on the annunciator panel, the high error rate would not apply.
10^{-1}	Personnel on different work shift fail to check condition of hardware unless required by check or written directive.
5×10^{-1}	Monitor fails to detect undesired position of valves, etc., during general walk-around inspection, assuming no check list is used.
0.2 - 0.3	General error rate given very high stress levels where dangerous activities are occurring rapidly.
$2^{(n-1)}x$	Given severe time stress, as in trying to compensate for an error made in an emergency situation, the initial error rate, x, for an activity doubles for each attempt, n, after a previous incorrect attempt, until the limiting condition of an error rate of 1.0 is reached or until time runs out. This limiting condition corresponds to an individual's becoming completely disorganized or ineffective.

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a. ODH Assessment Equations

The oxygen concentration in a confined volume during and after a release of an inert gas may be approximated with the following equations. Five Different cases are presented:

A. During release, with perfect mixing- Ventilation fan(s) blowing into the confined volume.

B. During release, with perfect mixing - Ventilation fan(s) drawing from the confined volume with the ventilation rate greater than the spill rate.

C. During release, with perfect mixing - Ventilation fan(s) drawing from the confined volume with the ventilation rate less than or equal to the spill rate.

D. After release, with perfect mixing.

E. Stratification of inerting gases

The equation and its solution are given which are based on an oxygen mass balance for the confined volume. The following definitions and assumptions are common for each case:

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)

Assumptions

* For case A through D complete and instantaneous mixing takes place in the confined volume. This is only a good assumption where gases have similar densities and/or mixing is "vigorous."

* Q, R, and V remain constant.

* Pressure in the confined volume remains constant and very near atmospheric pressure through the use of louvers or natural leakage.

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* Gas entering from outside the confined volume is air with an oxygen concentration of 0.21 (21%).

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

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

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

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

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

Case C During release - Ventilation fans(s) drawing contaminated atmosphere from the confined volume with the ventilation rate less than or equal to the spill rate (Q • R).

Differential equation for the oxygen mass balance

(5) $$V\frac{dC}{dt} = -R\,C$$

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

(6) $$C(t) = 0.21\,e^{-\frac{R}{V}t}$$

Case D After release - The oxygen concentration in the confined volume after the release has ended, $C_e(t)$, can be approximated by one equation.

Differential equation for the oxygen mass balance

(7) $$V\frac{dC}{dt} = 0.21\,Q - Q\,C$$

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Solution with the boundary condition of $C = C_r(t_e)$ at $t = t_e$

(8) $$C(t) = 0.21 - [0.21 - C_r(t_e)]\, e^{-\frac{Q}{V}(t - t_e)}$$

where $(t - t_e)$ is the time duration since the release ended.

Oxygen concentrations can be converted to partial pressures by:

(9) $$PO_2 = C\, P_a$$

where C = oxygen concentration

PO_2 = oxygen partial pressure (mmHg)

P_a = atmospheric pressure (mmHg)

(~ 740 mmHg at Fermilab)

Case E Stratification of inerting gases - The effects of stratification must be considered since inerting gases have different densities than air. The oxygen concentration can thus vary at various heights. Mixing conditions and building geometry can be used to estimate oxygen concentrations at various levels within an enclosure. Some of the earlier equations (1-9) still could be useful. For example, when a limited pocket volume has been identified, one could assume that perfect mixing applies within this limited volume. Then, by defining a ventilation case, the methods in Cases A-D can be applied.

b. ODH Hazard Classes

Once the ODH fatality rate (ϕ) has been determined, the operation shall be assigned an ODH class according to Table 4.

Table 4

Oxygen Deficiency Hazard Class		
ODH Class	$[\phi]$ (hr^{-1})	
0		$<10^{-7}$
1	$> 10^{-7}$ but	$<10^{-5}$
2	$> 10^{-5}$ but	$<10^{-3}$

Please note that areas intended to be entered by personnel during normal operations must be engineered to have an ODH Class of 2 or lower.

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An ODH risk assessment should include a discussion of each of the following:

1. Significant potential sources of reduced oxygen
2. Mechanisms
   - A. Spontaneous failures
   - B. Personnel-mediated failures
     - i) Operator error
     - ii) Accidents
3. Operations
   - A. Steady State
   - B. Other
     - i) Start up
     - ii) Repairs
     - iii) Special operations
     - iv) Shutdown
4. Gas dynamics
   - A. Ventilation
     - i) Natural
     - ii) Forced
   - B. Stratification/Mixing
   - C. Diffusion
5. The bases used for conclusions.

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2. ODH CONTROL MEASURES

Protective measures shall be implemented in a fashion which reduces the excess risk of fatality from exposure to an oxygen deficient atmosphere to no more than 10^{-7} per hour (Table 5). Alternate controls, such as area oxygen monitors in place of personal oxygen monitors, may be used where written justification has demonstrated that they provide an equal or superior level of safety. Since most controls are, themselves, subject to failure, their reliability must also be given appropriate consideration. For example, where a monitor-activated fan is used to reduce risk, the probability that the fan or monitor will fail must be included. An ODH control assessment should include a discussion of each of the following:

1. Environmental Controls
    - A. Ventilation
        - i) Forced
        - ii) Natural, including air makeup
    - B. Monitoring
        - i) Area oxygen monitoring
        - ii) Cryogenic systems
2. Personnel Controls
    - A. Posting
    - B. Entry control (locks, fencing, etc.)
3. Emergency Procedures
4. Special Requirements
    - A. Self-rescue supplied atmospheric respirators (escape packs)
    - B. Unusual procedures

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Table 5

ODH Control Measures		
ODH HAZARD CLASS	1	2
Environmental Controls		
1. Warning signs	X	X
2. Ventilation	X	X
ODH-Qualified Personnel Controls		
3. Medical approval as ODH qualified	X	X
4. ODH training	X	X
5. Personal oxygen monitor	X	X
6. Self-rescue supplied atmosphere respirator (escape pack)	X	X
7. Multiple personnel in communication		X
ODH-Restricted Personnel Controls		
8. Must not be ODH-excluded	X	X
9. ODH briefing	X	X
10. Self-rescue supplied atmosphere respirator (escape pack)	X	X
11. One-to-one escort by ODH qualified personnel	X	X
12. At least two ODH qualified personnel		X
X = Required		

KEY TO ODH CONTROL MEASURES

1. Warning signs - ODH signs shall be posted where they best serve to warn potentially exposed individuals. ODH signs are available from the ES&H Section

2. Ventilation - The minimum ventilation rate during occupancy should be established during the ODH risk assessment. This may be accomplished by any reliable means.

3. Medical approval as ODH qualified - This block of precautions shall only apply to individuals who have been classified as ODH-qualified by the Fermilab Medical Department.

4. ODH Training - Individuals shall receive training in oxygen deficiency hazards and safety measures associated with the operation. Annual retraining shall be required. Training is coordinated by the ES&H Section. Successful completion of an online challenge exam may be used to substitute for the annual retraining requirement.

5. Personal oxygen monitor - Individuals shall be equipped with a functioning

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calibrated personal oxygen monitor. Prior to each use they shall check that the displayed concentration is 21% in a normal atmosphere and the monitor is not past due for calibration. Personal oxygen monitors shall not be used beyond the last day of the month indicated on the calibration sticker. It is the responsibility of each division/section issuing personal oxygen monitors to have a program in place to insure that they are in compliance with this policy. It is the responsibility of ODH-qualified escorts to insure that the personal oxygen monitor(s) of those being escorted are not past due for calibration and are returned to the issuing organization or individual after use. Past-due monitors shall be returned to the individual or organization that issued it to arrange for recalibration.

All personal oxygen monitors used at Fermilab are set to alarm at the mandatory confined space limit of 19.5% (see Chapter 5063). This eliminates the need to maintain two "types" of personal oxygen monitors (one for ODH and one for confined spaces) as well as the associated potential for mismatching monitor and application.

Area oxygen monitors may be used in place of personal oxygen monitors where it has been demonstrated that they provide an equal or superior level of safety (e.g., where a high background noise level makes the personal oxygen monitor alarm imperceptible). Area ODH monitors are set to alarm at the ODH limit of 18% oxygen since there is no risk of misapplication with these fixed devices. (Alarm thresholds for area oxygen monitors may be set higher than 18% at the discretion of the division/section responsible for the ODH operation.)

Care must be exercised in the selection and use of oxygen monitors. Most instruments used in safety applications employ fuel cell type oxygen sensors. These devices consist of a diffusion barrier, a sensing electrode, a working electrode, and a basic electrolyte. The amount of current generated is proportional to the amount of oxygen consumed. There are two types of fuel cell sensors: capillary pore and membrane barrier. The former uses a narrow diameter tube through which oxygen diffuses into the sensor via capillary action. The latter depends on the partial pressure of oxygen to drive molecules through a membrane diffusion barrier into the sensor. In 2001, ES&H personnel at TJLab discovered that the response of capillary type cells can be non-linear when the displacing gas is helium. The nature of this non-linearity is such that the output of the cell is higher than it should be in an oxygen-deficient atmosphere. Therefore, alarms for a capillary cell monitor may not go off until the oxygen-concentration falls below the linearly-interpolation trip point for the instrument. This observation resulted in Fermilab replacing its capillary cell monitors with membrane diffusion monitors. The non-linearity effect appears to only occur when inerting gases have a lower molecular weight than that of air.

6. Self-rescue supplied atmosphere respirator (escape pack) - All individuals present shall have ready access to self- rescue supplied atmosphere respirators (escape packs) during the operation unless it has been demonstrated that they do

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not improve the probability of surviving an oxygen deficient atmosphere (e.g., when it takes longer to put on and activate the respirator than it does to escape the oxygen deficient environment).

7. Multiple personnel in communication - More than one individual shall be present; all of whom shall meet requirements (3), (4), and (5) above.

8. Must not be ODH-excluded - This block of precautions shall only apply to individuals who have not been classified as ODH-excluded by the Medical Department (such individuals are classified as ODH-restricted). Individuals classified as ODH-excluded shall not participate in any ODH Class 1 or greater operation.

9. ODH briefing - Individuals shall be briefed in oxygen deficiency hazards and safety measures of the operation prior to making entry into an ODH area.

10. Self -rescue supplied atmosphere respirator - Same as (6) above.

11. One-to-one escort by ODH-qualified personnel - An escort can be provided in special cases when the persons entering an area do not meet requirements 3 and 4. Individuals shall be under the direct continuous supervision of individuals who meet (3), (4), and (5) above. Note that escorted persons shall not have been designated as ODH-excluded by the Medical Department. If not evaluated by the Medical Department, the escort assumes responsibility for judging whether or not they believe the fitness of the escorted individual would significantly impede escape from the ODH operation in the event of an alarm.

12. At least two ODH-qualified personnel - Both (7) and (11) shall be followed when making entry into an ODH area.

Example designs of ODH signs are shown in Figure 2, which follows. Actual signs should be large enough to be easily read. They shall be posted where they best serve to warn potentially exposed individuals.

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Figure 2 - ODH signs

ODH Medical Surveillance

Medical surveillance shall be required to assure that persons engaged in ODH operations are adequately fit to escape from an oxygen deficient situation when properly warned. Hearing, vision, cardiopulmonary function, ambulatory abilities and mental stability shall all be considered in this respect.

A three level system of medical approval shall be used which gives the greatest operational freedom to those who are most fit (Table 6). The Medical Department shall be responsible for designating the level of approval via the "Medical Approval for Restricted Activities" form. Personnel who have not been reviewed by the Medical Department are considered "ODH-restricted."

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Table 6

Levels of ODH Medical Approval		
LEVEL	MEANING	DURATION OF APPROVAL
ODH-Qualified	Medically qualified to participate in all ODH Class 1 or greater operations	Typically 1-2 years based on the age and health status of the worker
ODH-Restricted	Medically qualified to participate in ODH Class 1 and ODH Class 2 operations when escorted by an ODH Qualified person	Typically 1-2 years based on the age and health status of the worker
ODH-Excluded	Prohibited from participation in any ODH Class 1 or greater operation	Until reclassified by the Medical Department

Procedures to Obtain

ODH Medical Approval from the

Medical Department

Fermilab Employees

1. Employees should contact the Medical Department to determine if a medical examination is necessary. In some instances existing health status information on file in the Medical Department is sufficiently current and complete to preclude the necessity for a pre-approval exam. In the event that an exam is needed, an appointment can be made at the time the employee contacts the Medical Department. Once an employee has been ODH-qualified, it is the responsibility of that employee to notify the Medical Department of any change in their health or medications which may affect their ODH qualification.

2. If an employee is found to be medically qualified, that information shall be entered into the TRAIN Database. In most cases, this entry will provide an adequate source of information for controlling access to ODH operations. The employee can also be issued an "Oxygen Deficiency Hazard Approval Card" for situations where a card would be helpful due to limited internet access. This card includes the name of the employee, their Lab ID number, and the name of their division/section. The Fermilab Physician signs and dates the "Medical Approval" section of this card as appropriate. Medical approval shall typically expire in one to two years, based on the age and health status of the worker.

Non-Employees (Including Users)

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1. The Fermilab representative for the non-employee shall arrange an appointment between the non-employee and the Fermilab Medical Department. If the non-employee is a contractor employee, then the representative shall notify the Contracts Department that ODH approval is being sought.

2. The Fermilab Physician shall decide what tests need to be performed so a decision can be made regarding the non-employee's fitness for ODH work and/or SCBA use. The Fermilab Physician shall determine whether the non-employee should be ODH-qualified and/or qualified for SCBA use.

3. If the non-employee is found fit, an "Oxygen Deficiency Hazard Approval Card" is issued by the Medical Department. The Fermilab Physician's name is signed and initialed by the nurse. The "Medical Approval for Restricted Activities" (LS/MED Form 7) is completed and forwarded as "distribution" indicates.

4. If the non-employee is found to be unfit for ODH work, the Medical Department will report this information to the Fermilab representative by telephone.

5. Medical approval for non-employee ODH/SCBA will expire in 1 year.

Respiratory Protection and ODH Approval Card

MEDICAL APPROVAL

ODH Restricted	Expires
_____	_____
_____	_____

SCBA	Expires
_____	_____
_____	_____

TRAINING

ODH	Expires
_____	_____
_____	_____
_____	_____

SCBA	Expires
_____	_____
_____	_____
_____	_____

Figure 3 - Respiratory protection and ODH approval card (optional)

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ODH Training

Individuals engaged in ODH class 1 or greater operations shall receive training in oxygen deficiency hazards and associated safety measures as outlined below. Annual retraining shall be required.

1. Normal Atmospheric Constituents
2. Effects of Exposure to Reduced Atmospheric Oxygen
    A. Reduced Abilities
    B. Loss of Consciousness
    C. Death
3. Sources and Mechanisms of Reduced Oxygen
4. ODH Safety Procedures
    A. Exposure Limit
    B. ODH Classification Scheme
    C. Required Controls
        1. Oxygen Monitors and Their Use
        2. Self-Rescue Supplied Atmosphere Respirators (escape packs)
        3. Medical Surveillance
        4. Other
    D. Evacuation and Rescue

For Lab employees, supervisors should arrange for ODH training through the ES&H Section. For non-employees, arrangements should be made by the Lab representative for the non-employee. "SCBA" training shall be required for all persons who must wear an SCBA (taught by the Fermilab Fire Department). A representative from the appropriate organization shall sign and date the "TRAINING" section of the "Oxygen Deficiency Hazard Approval Card."

Emergency Evacuation and Rescue

Emergency evacuation and rescue shall be conducted in accordance with the flow chart shown in

Figure 4 below. SRSAR stands for self-rescue supplied atmosphere respirator (escape pack). Individuals who have left an area due to an emergency may not re-enter until the emergency has ended and the area is known to be safe. That determination is to be made by the senior safety officer responsible for the area (or designee). Only the fire department is authorized to enter to perform a rescue. Local plans may differ slightly from that shown here.

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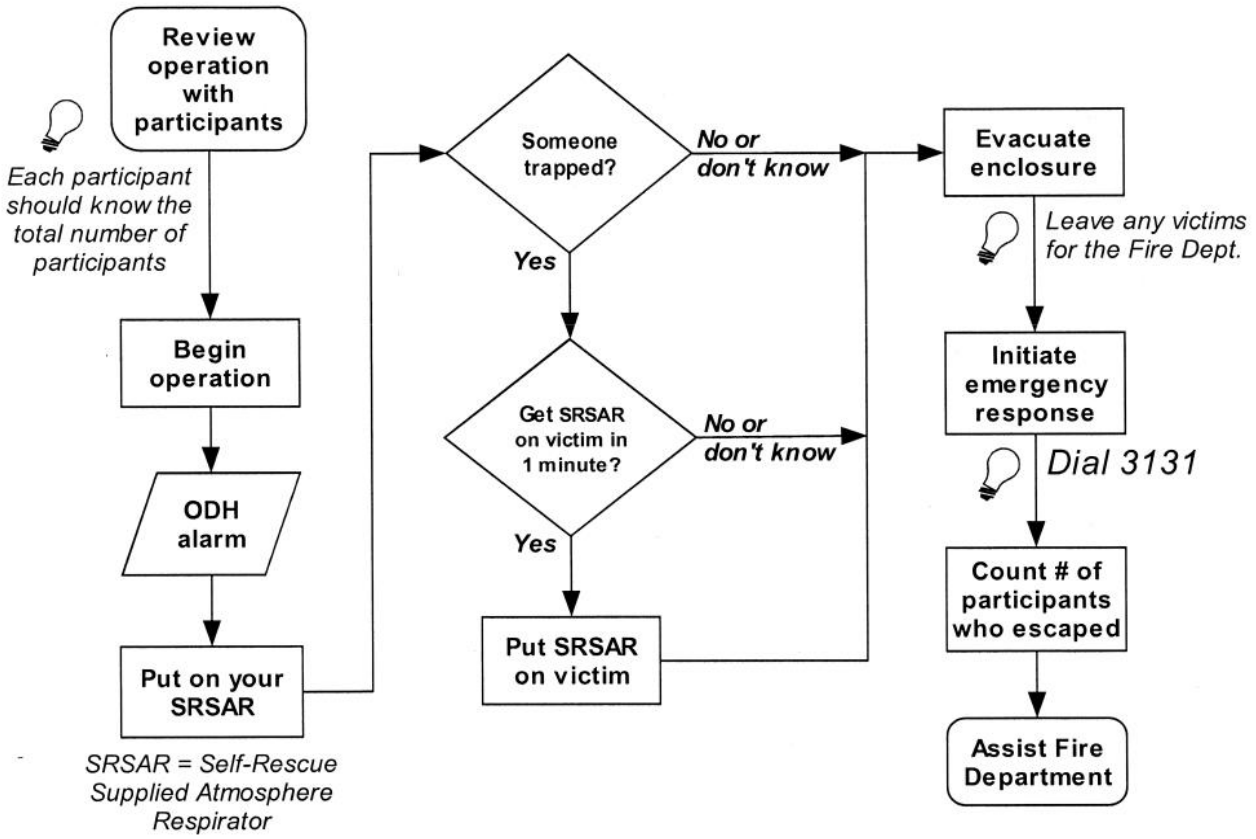

Figure 4 - Emergency evacuation and rescue

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Attachment 1

REFERENCE MATERIAL FOR OXYGEN DEFICIENCY HAZARDS

Effects of Exposure to Reduced Atmospheric Oxygen

Air normally contains about 21% oxygen with the remainder consisting mostly of nitrogen. (Although this section is written in terms of $\%O_2$ at sea level, the preferred index of hazard is partial pressure of O_2. Percent O_2 is used here to maintain consistency with the "readouts" on oxygen monitors. See Safety Note 12 which is available from the ES&H Section.) Individuals exposed to reduced-oxygen atmospheres may suffer a variety of harmful effects. Table 7 contains a list of some of these effects and the sea level oxygen concentrations at which they occur. At higher altitudes the same effects generally occur at greater volume concentrations since the partial pressure of oxygen is less. If exposure to reduced oxygen is terminated early enough, effects are general reversible. If not, permanent central nervous system damage or death result. Major effects hindering escape from the vicinity of an oxygen deficiency are disorientation and unconsciousness. Figure 5 is a plot of time of useful consciousness versus percent oxygen for seated individuals at sea level. For active individuals, the threshold for unconsciousness is 13%. Figure 6 shows the effect of oxygen deficiency on breathing, "error" rates, and vision.

In general, the intensities of the effects increase rapidly with falling oxygen concentration and longer exposure duration: reduced abilities, then unconsciousness, then death. While exposure to an atmosphere containing less than 17% oxygen presents some risk, it can be concluded that the 18% oxygen exposure limit provides an adequate margin of safety.

Table 7

Effect Thresholds for Exposure to Reduced Oxygen

(Seated Individuals at Sea Level)

Volume % Oxygen	Effects
17	Night vision reduced. Increased breathing volume. Accelerated heartbeat.
16	Dizziness. Time required for novel tasks doubled.
15	Impaired attention. Impaired judgment. Impaired coordination. Intermittent breathing. Rapid fatigue. Loss of muscle control.
12	Very faulty judgment. Very poor muscular coordination. Loss of consciousness. Permanent brain damage.
10	Inability to move. Nausea. Vomiting.
6	Spasmodic breathing. Convulsive movements. Death in 5 - 8 minutes.

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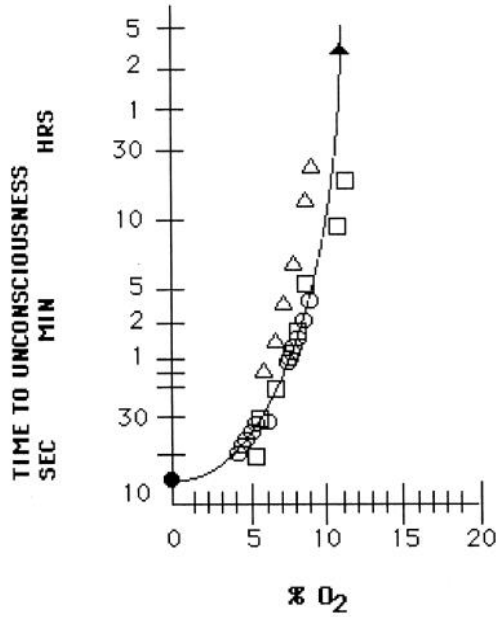

Figure 5 - Approximate time of useful consciousness as a function of oxygen concentration for seated subjects at sea level: Open squares and circles - duration of useful consciousness, Open triangles - time to coma, Filled triangles - threshold for unconsciousness, Filled circles - time to unconsciousness.

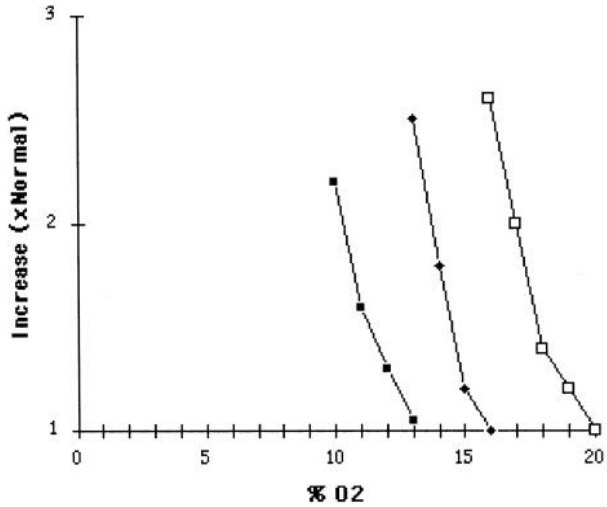

Figure 6 - Other effects as a function of oxygen concentration for seated subjects at sea level: Filled squares - volume of air breathed as a function of time, Filled diamonds - error rate (inverse of test scores for judgment, memory, and discrete movements), Open squares – required minimum illumination to see the same detail

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Attachment 2

Rationale for Table 1: "Fermilab Equipment Failure Rate Estimates"

B. Soyars

January 26, 2000

Table 1 in Chapter 5064 gives equipment failure rates based on Fermilab experience for a variety of systems. Rates are primarily based on data developed by the AD/Cryogenics Department. The large scale of this department's system allowed for many hours of operating time and experience. It's expected that similar systems in other departments will behave similarly. Differentiation will be made between a "leak" event and a "rupture" event.

1. Compressor (Two-stage Mycom)

The most typical ODH events related to compressors are leaking lines. A typical event is a leak in the 3/8" oil control lines for slider positioning, which leads to oil, oil mist, and helium venting within the compressor building. This has occurred about 8 times resulting in about 5 ODH alarms. It's somewhat questionable whether it was low oxygen or the presence of oil mist that set off the alarm, but since inerting gas is present in carrying the mist, assume the alarm response was real. All these events had potential for causing ODH conditions and therefore will be tallied as ODH events. Another less common reason is the opening of unvented pockets during maintenance. This has happened perhaps twice. It's possible that compressor building ODH events could be under-reported since these non-cryogenic events typically have little or no impact on accelerator operations. Thus, it seems plausible to increase the leak event total number by 50%, from 10 to 15. There have been through January 1999 125,000 hours with the He header system live and compressors operating. Then, for leaks:

$$\text{failure rate} = \frac{15}{\left(1.25\times10^{5}\ \text{hr}\right)\times 25\ \text{cmprs}} = 5\times10^{-6}\ /\text{hr}$$

A similar number for rupture is more difficult to determine since no real rupture events have been recorded. Nevertheless, by assuming one rupture failure, an upper limit to this failure rate can be estimated:

$$\text{failure rate} = \frac{1}{\left(1.25\times10^{5}\ \text{hr}\right)\times 25\ \text{cmprs}} = 3\times10^{-7}\ /\text{hr}$$

2. Dewar

A wide variety of dewars are operated at Fermilab and much dewar experience has been gained. (Note, information outside of AD/Cryogenics will be considered here). A typical major failure mode is when the insulating vacuum shell gets cracked leading to the loss of vacuum to air and the potential for significant venting of warmed-up

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cryogens. Consider a failure that occurred at MTF (January 1997) in which a 10,000 gal nitrogen dewar had its vacuum shell cracked due to cold shocking. This occurred after 5.5 years of it being in service. This was the only failure over this time period for an assumed average of 20 dewars in continuous service. Take this 5.5 years as typical mean time between failure for a lot of 20 dewars. Then the failure rate would be:

$$\text{failure rate} = \frac{1}{\left(4.8\times10^{4}\ \text{hr}\right)\times 20\ \text{dewars}} = 1\times10^{-6}\ /\text{hr}$$

This predicted value rate matches what was originally used in Table 1, indicating that it seems to be a fair value to use for dewar failure rates. Further laboratory experience can be considered in a more anecdotal fashion. A few other similar failures have occurred during the 30 year lab history. About two more cold shock failures have occurred, and about two more 500 liter portable dewars have lost vacuum (one at Lab 2 when dropped from a truck, another in the Village). Consider then five failures for 20 dewars in continuous service during a 30 year period. This produces a failure rate identical to the above calculation. This supports the above analysis being indeed typical.

3. Electrical Power Failure

The original Table 1 gives this failure rate as 1 E-4 /hr, and 3 E-4 /demand.

This existing time failure rate comes out to about 1 per year, which is in agreement with experience.

4. Fluid line (Cryogenic)

Assume this category includes fittings, valves, seals, and O-rings. Failures of this nature have been the most commonly encountered cause for AD/Cryogenics ODH events. An example is temperature related seal failures. AD/Cryogenics data has estimated about 30 total ODH events from 1983-1988, and <15 events from 1989-1996. Since we have documented 16 tunnel spill events, let's assume there have been about 30 of the 45 total events falling into this category of cryogenic fluid lines.

Through January 1999 there were 105,000 Tevatron cryogenic system hours cold. Assume 24 refrigerator buildings each with 25 fittings (bayonets and reliefs). Then the leak failure rate for a fluid line or fitting is:

$$105{,}000\ \text{hrs}\times 24\ \text{bldgs}\times 25\ \text{ftg/bldg} = 63\times10^{6}\ \text{ftg - hrs}$$

$$\text{failure rate} = \frac{30}{63\times10^{6}} = 5\times10^{-7}\ /\text{hr}$$

Rupture failures, such as a bayonet blowing out, are more difficult to determine since no real rupture events have been recorded. Nevertheless, by assuming one rupture failure, an upper limit to this failure rate can be estimated:

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$$\text{failure rate} = \frac{1}{\left(63\times10^{6}\ \text{hr}\right)} = 2\times10^{-8}\ /\text{hr}$$

5A. Magnet (cryogenic)

Let's look at magnets under two separate conditions. First consider cold and powered magnets. Personnel are not working near the magnets under these circumstances. Up to January 1999, there have been 63,000 hours of Tevatron system powered conditions. There have been 11 magnet spill events mostly, if not all, due to single-phase rupture to vacuum from an electrical fault. Then magnet "powered, unmanned" failure rate is:

$$\text{failure rate} = \frac{11}{63000\times1000\ \text{magnets}} = 2\times10^{-7}\ /\text{hr}$$

5B. Magnet (unpowered, could be cryogenic conditions, could be warm)

A separate condition for the magnets are when they are not powered. This assumes that manned activity is occurring around the magnets which either are cold, or are warm with inerting gases present. These conditions have produced 2 potential ODH events. Both of these recorded failures were magnet Kautzky valves getting hit. In fact, the valves remained intact and no spill occurred; but nonetheless, since there was potential, these have been counted as ODH events. There have been 89,000 hours of Tevatron system not powered. Then magnet "not powered, manned" failure rate is:

$$\text{failure rate} = \frac{2}{89000\times1000\ \text{magnets}} = 2\times10^{-8}\ /\text{hr}$$

6. Header Piping Assembly

Three ODH events were observed that were related to the helium header piping. The failure rate will be based on failures per vulnerable or accessible assembly. In these failure cases, the vulnerable assembly was a flex hose attached to the header. Note that two of these were the failures discussed in 5B, which could have led to exposure of either the header or the magnet inventory (or both). Therefore, those events will be counted in both categories. One additional event involved the header opening up during a magnet change when an incorrect maintenance procedure let an uncapped Kautzky valve leak when its control pressure line was broken. For the header in the Tevatron, there are about 70 flex hose connections to the header for one house. From the known header operating time of about 125,000 hours, we get a failure rate per piping assembly:

$$\text{failure rate} = \frac{3}{125000\times70\times24} = 1\times10^{-8}\ /\text{hr}$$

7. U-Tube change

Procedures reduce the ODH impact of problems during U-tube changes by minimizing

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the exposure to large sources. For example, isolation valves are closed and the system depressurized before the pull. So when problems or failures have occurred, they have procedurally been prevented from falling into the ODH event category. Thus, AD/Cryogenics doesn't really offer any ODH statistics for altering the original 5064 failure rate estimates (3×10^{-2}/D small event, 1×10^{-3}/D large event).

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2. ODH Statistics, J. Theilacker, October 3, 1988.

3. Discussion of Known ODH Events, W. Soyars, April 18, 1996.

4. Email from Tom Peterson, "Dewar Failure Rates," January 26, 2000.

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