OXYGEN DEFICIENCY HAZARDS (ODH)

RHIC PROJCECT

I. INTRODUCTION

Persons exposed to reduced-oxygen atmospheres may experience adverse health consequences, including unconsciousness, or death. The purpose of this Standard is to describe the methodology for assessing the potential for an oxygen deficient environment and controlling the associated hazards.

II. APPLICABLE STANDARDS

None

III. DEFINITIONS

mmHg - millimeters of mercury representing or measuring a pressure by relating it to the weight of a liquid mercury column.

Oxygen Concentration - the molar fraction of a gaseous mixture represented by oxygen. It is also equal to the ratio of the partial pressure of oxygen to the total mixture pressure.

Oxygen Deficiency - the condition when the partial pressure of atmospheric oxygen is less than 137 mmHg (about 18% by volume at a barometric pressure of 760 mmHg).

Partial Pressure - the pressure due to one of several components of a gaseous mixture. The sum of component partial pressures equals the mixture pressure.

Self-Rescue Supplied Atmosphere Respirator - a device containing breathing air to be used for escape during an ODH event.

Shall - implies a requirement without deviation.

Should - implies discretion can be used.

IV. RESPONSIBILITIES

The Project Head in conjunction with the S&EP Division is responsible for determining the applicability of this Standard to the systems and areas under his/her responsibility. The S&EP Division shall administer the purchase and maintenance of personal oxygen monitors.

V. PROCEDURES

A. A quantitative assessment of the fatality risk potential from exposure to oxygen deficient atmosphere shall be conducted for all operations which are physically capable of exposing personnel to such a hazard. This assessment shall specify the Oxygen Deficiency Hazard Class as well as any unusual precautionary requirements. Attachment 1 entitled "ODH Risk Assessment" shall be used to conduct the assessment.

B. Control measures shall be implemented according to the ODH Class unless otherwise stated in the risk assessment. ODH Class 0 is the least hazardous and requires no special precautions. ODH Class 4 is the most hazardous and requires the most extensive precautions. Attachment 2 entitled "ODH Control Measures" shall be used to control the potential ODH hazard.

APPROVED Satoshi Ozaki _____ **DATE** 1/5/98 _____
RHIC Project Head

ODH RISK ASSESSMENT

The goal of ODH risk assessment is to estimate in the fatality rate due to exposure to oxygen deficient atmosphere.

Since the level of risk is tied to the nature of the operation, the excess fatality rate shall be determined on an operation-by-operation basis. For a given 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 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 fatality factor for the ith event.

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 from empirical data; otherwise data from similar systems or other relevant referencable values shall be used.

The value of F_i is the probability that a fatality will result if the ith event occurs. The value depends on the oxygen concentration, the duration of exposure and the difficulty of escape. For convenience of calculation, Figure A-1 defines the relationship between the value of F_i and the lowest attainable oxygen concentration. This relationship should be used when no better estimate of the probability of fatality from a given event is available. The lowest concentration is used rather than an average. If the lowest oxygen concentration is greater than 18% (~ 137 mmHg), 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. If the lowest attainable oxygen concentration is 18%, then the value of F_i is 10^{-7}. This value would cause F to equal zero at 10^{-7} per hour. If the expected rate of occurrence of the event were 1 per hour, then F=1. 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% (~ 67 mmHg) oxygen, the concentration at which one minute of consciousness is expected.

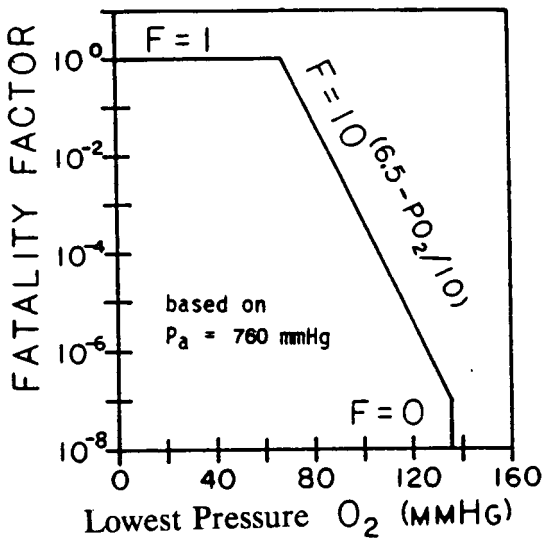


Figure A-1. Graph of the logarithm of the fatality factor (F_i) versus the lowest attainable oxygen concentration which can result from a given event.

The oxygen concentration in a confined volume during and after a release of an inert gas may be approximated for three different cases:

A. Ventilation fan(s) blowing into the confined volume.

B. Ventilation fan(s) drawing from the confined volume with the ventilation rate greater than the spill rate.

C. Ventilation fan(s) drawing from the confined volume with the ventilation rate less than or equal to the spill rate.

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

Definitions

C	=	oxygen concentration
C_r	=	oxygen concentration during the release
C_e	=	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

- Complete and instantaneous mixing takes place in the confined volume.
- 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.
- Gas entering from outside the confined volume is air with an oxygen concentration of 0.21 (21% by volume).

Case A Ventilation fan(s) blowing into the confined volume.

The differential equation for the oxygen mass balance is:

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

The solution for the boundary condition of C=0.21 at t=0 is:

$$C_r(t) = \left[\frac{0.21}{Q+R}\right]\{Q+Re^{[-(Q+R)t/V]}]$$

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

The differential equation for the oxygen mass balance is:

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

The solution with the boundary condition of C=0.21 at t=0 is:

$$C_r(t) = 0.21\left[1-\frac{R}{Q}[1-e^{[-Q\,t/V]}]\right]$$

<u>Case C</u> <u>Ventilation fan(s) drawing from the confined volume with the ventilation rate less than or equal to the spill rate</u>.

Differential equation for the oxygen mass balance is:

$$V\frac{dC}{dt} = -RC$$

The solution with the boundary condition of C=0.21 at t=0 is:

$$C_r(t) = 0.21e^{[-Rt/V]}$$

The oxygen concentration in the confined volume after the release has ended, $C_e(t)$, can be approximated by one equation for all three cases.

The differential equation for the oxygen mass balance is:

$$V\frac{dC}{dt} = 0.21Q-QC$$

The solution with the boundary condition of $C=C_r(t_e)$ at $t=t_e$, where $(t-t_e)$ is the time duration since the release ended is:

$$C_e(t) = 0.21-[0.21-C_r(t_e)]\,e^{[-Q(t-t_e)/V]}$$

Oxygen concentrations can be converted to partial pressures by,

$$Po_2 = CP_a$$

where C = oxygen concentration (volume %)
Po_2 = oxygen partial pressure (mmHg)
P_a = atmospheric pressure (mmHg), approximately 760 mmHg at BNL

Once the ODH fatality rate (Φ) has been determined, the operation shall be assigned an ODH class according to Table A-I.

TABLE A-I

OXYGEN DEFICIENCY HAZARD CLASS

ODH Class (Fatalities/Hr)	
0	$<10^{-7}$
1	$\geq 10^{-7}$ but $<10^{-5}$
2	$\geq 10^{-5}$ but $<10^{-3}$
3	$\geq 10^{-3}$ but $<10^{-1}$
4	$\geq 10^{-1}$

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

1. Significant potential sources of reduced oxygen

2. Mechanisms

   A. Equipment failures

   B. Personnel-initiated 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 conclusion.

ODH CONTROL MEASURES

Protective measures shall be implemented to reduce the risk of fatality from exposure to an oxygen deficient atmosphere to no more than 10^{-7} per hour. The matrix in Table B-I describes the minimum control measures to allow an individual to participate in a given ODH Class. Alternate procedures (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.

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) Posting
      iii) Entry control (locks, fencing, etc.)

2. Personnel Controls

3. Special Requirements

   A. Self-rescue supplied atmospheric respirators

   B. Unusual procedures.

TABLE B-I

ODH CONTROL MEASURES

	ODH Hazard Class			
Environmental Controls	1	2	3	4
1. Warning signs	X	X	X	X
2. Ventilation	X	X	X	
ODH Qualified Personnel Controls				
3. Medical approval as ODH qualified	X	X	X	X
4. ODH training	X	X	X	X
5. Personal oxygen monitor	X	X	X	
6. Self-rescue supplied atmosphere respirator	X	X	X	
7. Multiple personnel in communication		X		
8. Unexposed observer			X	
9. Self-contained breathing apparatus				X
ODH Restricted Personnel Controls				
10. Must not be ODH excluded	X	X	NA	NA
11. ODH briefing	X	X	NA	NA
12. Self-rescue supplied atmosphere respirator	X	X	NA	NA
13. One-to-one escort by ODH qualified personnel	X	X	NA	NA
14. At least two ODH qualified personnel		X	NA	NA

X = Required
NA = Not applicable, ODH restricted personnel shall not be exposed to ODH Class 3 or Class 4 operations

KEY TO ODH CONTROL MEASURES

1. Warning Signs - ODH signs shall be posted to warn potentially exposed individuals. ODH signs are available from the S&EP Division.

2. Ventilation - The minimum ventilation rate during occupancy should be at least one volume change per hour. This may be accomplished by any reliable means.

3. Medical Approval as ODH Qualified - These precautions shall only apply to individuals who have been classified as ODH qualified by the Occupational Medical Clinic (OMC).

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 the responsibility of the Department/Division in charge of operations.

5. Personal Oxygen Monitor - Personal oxygen monitors shall not be used beyond the date they are due for recalibration. Each monitor shall have a unique identifying number and a sticker indicating the date due for calibration. The calibration due date is to be the last day of the month indicated on the calibration sticker. It is the responsibility of the Department/Division 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 an ODH-qualified individual using a personal oxygen monitor to inspect the calibration sticker on the monitor before use and insure that the monitor is not past due for calibration. A past-due monitor shall not be used. It shall be returned to the individual or organization who issued it to arrange for recalibration. It is the responsibility of an ODH-qualified escort 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. A past-due monitor shall not be used. It shall be returned by the escort to the individual or organization who issued it to arrange for recalibration.

6. Self-Rescue Supplied Atmosphere Respirator - Individuals shall have ready access to self-rescue supplied atmosphere respirators during the operation unless this requirement was found to be inappropriate in the risk analysis.

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

8. Unexposed Observer - All personnel engaged in the operation shall be in continuous communication with an observer who cannot be exposed to an oxygen deficiency. The purpose of the observer shall be to summon the Fire/Rescue Group in case of need.

9. Self-Contained Breathing Apparatus - Individuals shall be wearing a self-contained breathing apparatus (SCBA) during the operation. Prior designation as medically fit to wear an SCBA by the OMC is required before training in SCBA.

10. Must Not Be ODH Excluded - These ODH control measures shall only apply to individuals who have not been classified as ODH excluded by the OMC (such individuals are classified as ODH restricted). Individuals classified as ODH excluded shall not participate in any ODH Class.

11. ODH Briefing - Individuals shall be briefed in oxygen deficiency hazards and safety measures of the operation.

12. Self-Rescue Supplied Atmosphere Respirator - Same as (6) above.

13. One-to-One Escort By ODH Qualified Personnel - Individuals shall be under direct continuous supervision of individuals who meet (3), (4), and (5) above. There shall be at least one escort for ODH restricted person.

14. At Least Two ODH Qualified Personnel - Both (7) and (13) shall be followed.

ODH SIGNS

The design of ODH signs is shown in Figure B-1 below. They shall be posted where they best serve to warn potentially exposed individuals.

Figure B-1

ODH Medical Surveillance

The OMC will determine fitness to engage in ODH environments as specified by the RHIC Project.

A Job Assessment Form shall be completed by the supervisor and forwarded to the OMC prior to the periodic examination. The RHIC Project supervisor will be advised if there are any limitations on an employee's job activities.

PROCEDURES TO OBTAIN ODH MEDICAL APPROVAL FROM THE OCCUPATIONAL MEDICAL CLINIC (OMC)

1. Supervisor notifies the OMC via a Job Assessment Form that the employee will require access to ODH Class 1 or 2 areas.

2. The employee is evaluated for ODH work during the routine OMC physical examination. The OMC shall notify the supervisor if any limitation(s) are applicable to the employee.

3. Supervisor (or employee) schedules the employee to attend RHIC ODH training class by contacting the RHIC Training Group.

4. Employee attends class, passes examination.

5. RHIC Training Group enters the employee into the RHIC training database.

6. RHIC Training Group notifies employee as training certification expiration approaches. Supervisor or employee schedules refresher training with RHIC Training Group.

7. RHIC Training Group periodically provides the OMC with a list of personnel who shall be maintained in the ODH protocol. The OMC shall advise the Project on the status of those employees in response to requests from RHIC.

8. Supervisors are responsible for making sure that employees complete their routine physical examinations as scheduled.

<u>ODH Training</u>

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 Oxygen Deficient Atmosphere

   A. Reduced Abilities
   B. Loss of Consciousness
   C. Death

3. Causes Producing Oxygen Deficient Atmosphere

4. ODH Safety Procedures

   A. Exposure Limit
   B. ODH Classification Scheme
   C. Required Controls

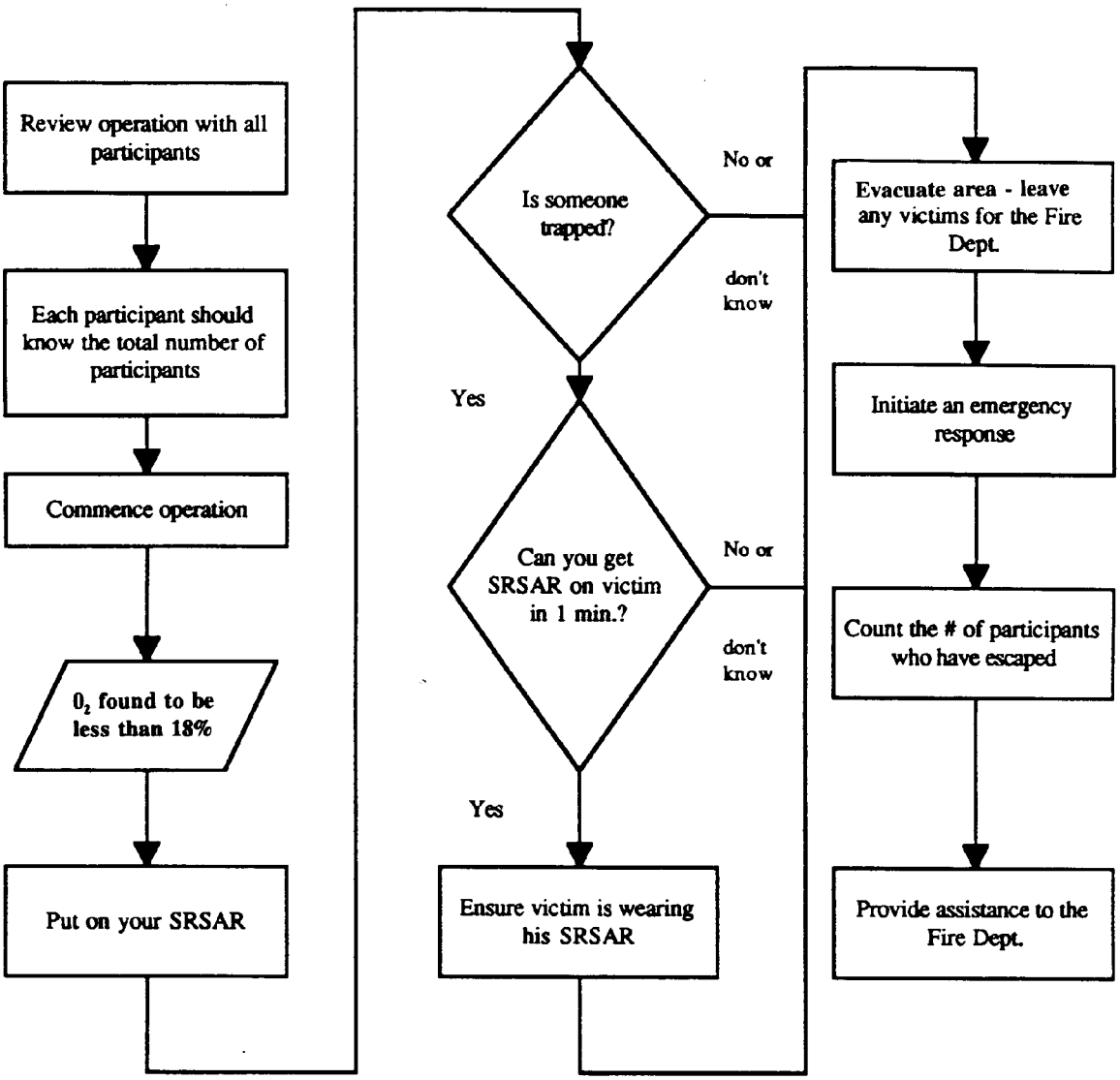
      1. Oxygen Monitors and Their Use
      2. Self-Rescue Supplied Atmosphere Respirators
      3. Medical Surveillance
      4. Other

   D. Evacuation and Rescue

For BNL employees, supervisors should arrange for ODH training though the Training Coordinator having jurisdiction over the ODH operation(s) of interest. For non-employees, arrangements should be made by the BNL representative for the non-employee. SCBA training shall be required for all persons who must wear an SCBA.

EMERGENCY EVACUATION AND RESCUE

Emergency evacuation and rescue shall be conducted in accordance with the flow chart shown below. SRSAR stands for self-rescue supplied atmosphere respirator. Local plans may differ slightly from that shown here.



TYPICAL MEASURES FOR COMMONLY ENCOUNTERED ODH CLASS 0 AND CLASS 1 OPERATIONS

A. Environmental Controls

1. The least ventilation rate during occupancy should be at least one volume change per hour accomplished by any reliable means. Appropriate ODH warning signs shall be posted where they best serve to warn potentially exposed individuals (available from the S&EP Division, see below).

CAUTION

OXYGEN DEFICIENCY HAZARD

0

PRIOR TO ENTRY, ALL
PERSONNEL MUST HAVE THE FOLLOWING:
• OXYGEN DEFICIENCY HAZARD ORIENTATION

CAUTION

OXYGEN DEFICIENCY HAZARD

1

PRIOR TO ENTRY, ALL
PERSONNEL MUST
HAVE THE FOLLOWING:
• A PERSONAL OXYGEN MONITOR
• A SELF-RESCUE SUPPLIED ATMOSPHERE RESPIRATOR
• OXYGEN DEFICIENCY HAZARD TRAINING
• MEDICAL APPROVAL FOR OSYGEN DEFICIENTY HAZARD WORK

2. Other controls such as centralized check-in and check-out or area oxygen monitors may be locally required.

B. Personnel Controls

The following shall be required prior to participation:

1. Medical approval shall be obtained to assure that persons engaged in ODH operations are medically fit to escape from an oxygen deficient situation when properly warned. It may be necessary to have an examination by the OMC in order to secure approval.

2. ODH training shall be obtained which is pertinent to the operation. Annual re-training shall be required. Documentation of training status may be required via ODH Approval Card. Check with the Training Coordinator of the Department/Division controlling the ODH operation to schedule training or for further clarification. It is therefore important for employees to complete scheduled physical examinations at the OMC.

3. A properly operating portable oxygen monitor shall be used by persons participating in the ODH operation. This requirement may be waived if shown to be inappropriate in the risk assessment.

4. A self-rescue supplied atmosphere respirator shall be readily available to each person participating in the ODH operation. This requirement may be waived, if shown to be inappropriate in the risk assessment.

5. Special requirement for ODH Class 2 operations. In addition to the above requirements, there shall be at least two persons present at the operation who are in continuous communication and who meet the requirements above.

6. Special requirements for persons not meeting requirements 3 and 4 above. Such persons shall not have been designated as ODH excluded by the OMC (documentation of medical approval status may be required as in 3). If not evaluated by the OMC, such persons shall be evaluated by a representative of Department/Division management controlling the ODH operation (e.g., ES&H staff) to exclude individuals who obviously do not meet minimum approval status (ODH Restricted). Such persons shall also meet requirement 5 and shall be escorted, one-to-one, by persons meeting requirements 3 and 4.

7. Supervisors are responsible for requesting reevaluation by the OMC, where there may be changes in health status or fitness for duty which could be adversely affected by an ODH atmosphere.

REFERENCE MATERIAL FOR OXYGEN DEFICIENCY HAZARDS

Effects of Exposure to Reduced Atmospheric Oxygen

The use of compressed gases, liquefied gases, and volatile liquids is commonplace at BNL. Introduction of these materials to the atmosphere can present a hazard. In particular, oxygen deficiency is important for those materials which are neither acutely toxic nor flammable.

Air normally contains about 21%* oxygen with the remainder consisting mostly of nitrogen. Individuals exposed to reduced-oxygen atmospheres may suffer a variety of harmful effects. Table B-III 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 lethality result. Major effects hindering escape from the vicinity of an oxygen deficiency are disorientation and unconsciousness. Figure B-3 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 B-4 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. It can be concluded that any exposure to an atmosphere containing less than 17% oxygen presents a risk, therefore OSHA regulations require alarm set points at 19.5% to avoid exposure to $\leq$18%.

Although this section is written in terms of volume percent 0_2 at sea level, the preferred index of hazard is partial pressure of 0_2. Volume percent 0_2 is used here to maintain consistency with the "readouts" on oxygen monitors.

TABLE B-III

EFFECT THRESHOLDS FOR EXPOSURE TO REDUCED OXYGEN
(Normal Individuals at Rest at Sea Level)

Volume % Oxygen	Effect
17	Night vision reduced Increased breathing volume Accelerated heartbeat
16	Dizziness Increased time doubled for novel tasks
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

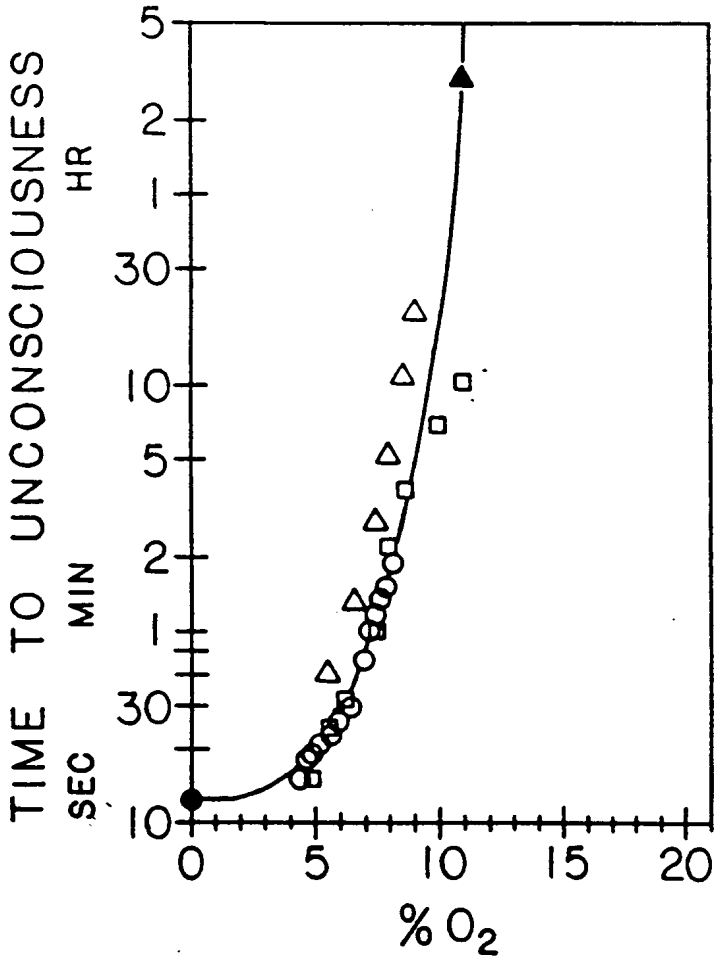


Figure B-3. Approximate time of useful consciousness as a function of oxygen concentration for seated subjects at sea level.

□ Duration of useful consciousness.
◦ Duration of useful consciousness.
△ Time to coma.
▲ "Threshold" for unconsciousness.
• Time to unconsciousness.

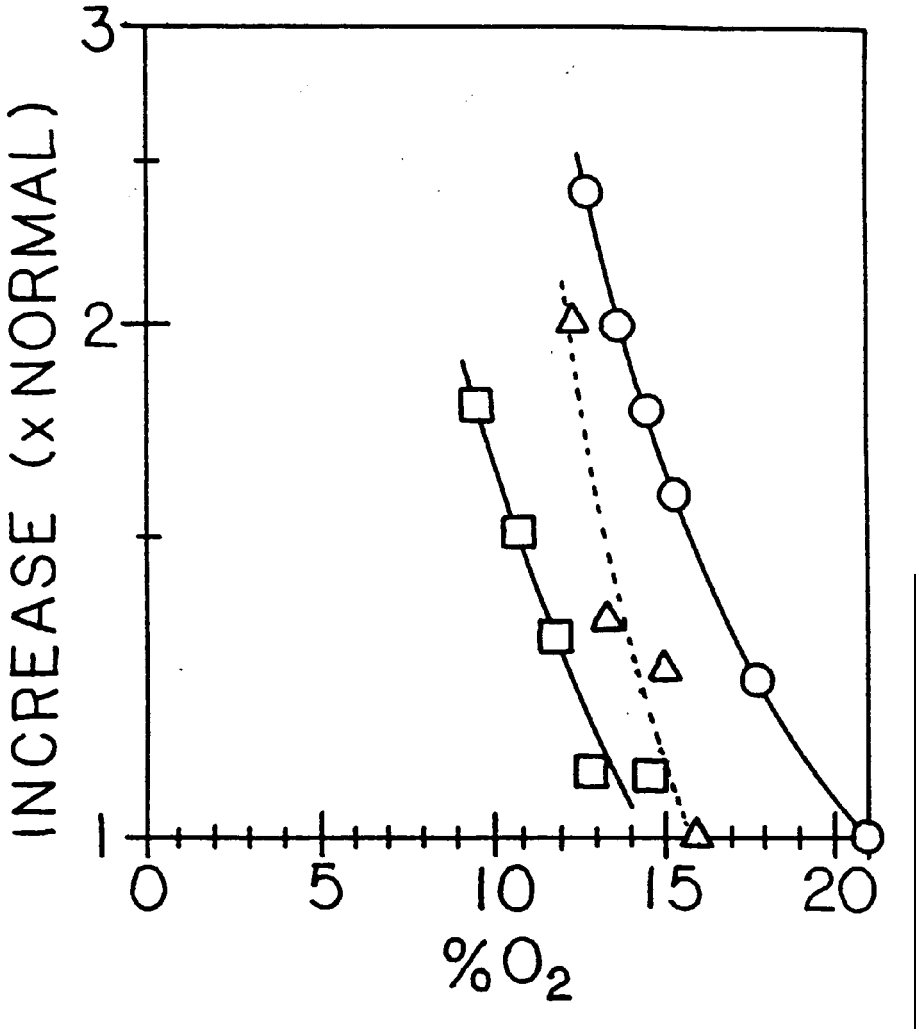


Figure B-4. Other effects as a function of oxygen concentration for seated subjects at sea level.

□ Volume of air breathed as a function of time.
△ "Error" rate (inverse movements).
◦ Required minimum illumination to see the same amount of detail.

EQUIPMENT FAILURE AND HUMAN ERROR RATES

Additional Risk Assessment Data

Estimates of cryogenic equipment failure rates are given in Table B-IV. These data are median estimates collected from past ODH risk assessments performed on systems at Fermilab.

Failure rates for various equipment types derived from the nuclear power industry that may be useful as input data are shown in Table B-V.

General human error rate estimates are presented in Table B-VI. Table B-VII lists conservative estimates of the rate of human error as a function of task type and time limit.

TABLE B-IV

FERMILAB EQUIPMENT FAILURE RATE ESTIMATES

Failure Mode		Estimated Median Failure Rate
Compressor (Cryogenic)	Leak or Rupture	3×10^{-5}/HR
Dewar	Leak or Rupture	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 or Rupture	3×10^{-6}/HR
Magnet (Cryogenic)	Leak or Rupture	1×10^{-6}/HR
Change of Equipment with Bayonet Fitting (Cryogenic Release)	Small Event Large Event	3×10^{-2}/D 1×10^{-3}/D

TABLE B-V

U.S. NRC EQUIPMENT FAILURE RATE ESTIMATES

FAILURE MODE		MEDIAN FAILURE RATE
Batteries Power Supplies	NO/Output	$3x10^{-6}$/HR
CIRCUIT BREAKERS	Failure to Operate	$1x10^{-3}$/D
	Premature Transfer	$1x10^{-6}$/HR
Diesel (Complete Plant) (Emergency Loads) Diesel (Engine Only)	Failure to Start Od:	$3x10^{-2}$/D
	Failure to Run	$3x10^{-3}$/HR
	Failure to Run	$3x10^{-4}$/HR
ELECTRIC MOTORS	Failure to Start	$3x10^{-4}$/D
	Failure to Run	$1x10^{-5}$/HR
	Failure to Run (Extreme ENVIR)	$1x10^{-3}$/HR
FUSES	Premature, Open	$1x10^{-6}$/HR
	Failure to Open	$1x10^{-5}$/D
Gaskets	Leak	$3x10^{-6}$/HR
Flanges, Closures, Elbows	Leak/Rupture	$3x10^{-7}$/HR
Instrumentation (Amplification, Annuciators, Transducers, Calibration, Combination)	Failure to Operate	$1x10^{-6}$/HR
	Shifts	$3x10^{-5}$/HR
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/NC Contact	$1x10^{-8}$/HR
	Open NC Contact	$1x10^{-7}$/HR
SOLID STATE DEVICES HI PWH 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 Short	$1x10^{-8}$/HR

FAILURE MODE		MEDIAN FAILURE RATE
TRANSFORMERS	Open CKT	$1x10^{-6}$/HR
	Short	$1x10^{-6}$/HR
Valves: MOV.	Fails to Operate	$1x10^{-3}$/D
	(Plug) 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	$3x10^{-4}$/D
	(Plug) 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
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	$1x10^{-5}$/D
	Premature Open/HR	$1x10^{-5}$/HR
Welds	Leak	$3x10^{-9}$/HR
WIRES	Open	$3x10^{-6}$/HR
	Short to GND	$3x10^{-7}$/HR
	Short to PWR	$1x10^{-8}$/HR

TABLE B-VI

HUMAN ERROR RATE ESTIMATES

Estimated 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.
.2 - .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.

TABLE B-VII

HUMAN ERROR RATE AS A FUNCTION OF RESPONSE TIME

Response Times (sec)

Maximum Estimated Error Rate (D^{-1})	Skill Based Task	Rule Based Task	Knowledge Based Task
10^{-4}	37	600	18,000
10^{-3}	26	300	10,000
10^{-2}	16	130	4,900
10^{-1}	8.7	42	1,800
5×10^{-1}	4.0	10	550

Skill Based Task - An individual initiates a single-step learned response upon receipt of an unambiguous sensor cue. (Example: A lone worker initiates escape upon hearing an oxygen deficiency alarm).

Rule Based Task - An individual or small group of individuals diagnoses and initiates corrective actions for a simple problem given limited or ambiguous input. (Example: Several workers decide whether or not to escape, given that one of them passes out but no oxygen deficiency alarms sound.)

Knowledge Based Task - A group of individuals diagnoses and initiates corrective actions for a novel and/or complex problem.