ESS Guideline for Oxygen Deficiency Hazard (ODH)

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1. PURPOSE

The purpose of this guideline is to specify requirements and to provide guidance on methodologies for assessing the potential risk and to reduce risk associated with hazards due to a possible oxygen deficient environment.
This guideline is aligned with ESS Procedure for Systematic Work Environment Management, ESS 0051380 [1]

The use of compressed and liquefied asphyxiant gases such as helium and nitrogen is common at ESS. The release of these elements into the atmosphere can present a risk, in particular to persons exposed to reduced-oxygen atmospheres. Under these conditions persons may experience reduced abilities, unconsciousness, or death.

Two factors make Oxygen Deficiency Hazards (ODH) so dangerous. The first is the large volume ratio between a cryogenic liquid and its gaseous state at room temperature and pressure. As an example 1 litre of liquid nitrogen will result in 700 litres of nitrogen gas at room temperature and pressure. Thus, it takes a small amount of cryogenic liquid vented into a space to reduce the oxygen concentrations to dangerous levels. Second, in low enough oxygen concentrations the first physiological symptoms of a problem can be unconsciousness, coma and death. Unconsciousness can occur in less than 30 seconds.

2. SCOPE

This ODH safety process applies to any activity/ area/ equipment at ESS involving the use of asphyxiant fluids that could have an impact on people’s safety.

3. DEFINITIONS

Oxygen deficiency: any condition under which the partial pressure of atmospheric oxygen is less than 135 mmHg or about 18% oxygen concentration.

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 in the mixture. The oxygen concentration in normal ambient atmosphere is 20.9%.

Oxygen deficiency Hazard: any activity that may expose personnel to an increased risk due to oxygen deficiency.

4. REGULATORY FRAMEWORK

Any activity/area/equipment involving the use of asphyxiant fluids shall comply with the following regulations and standards:

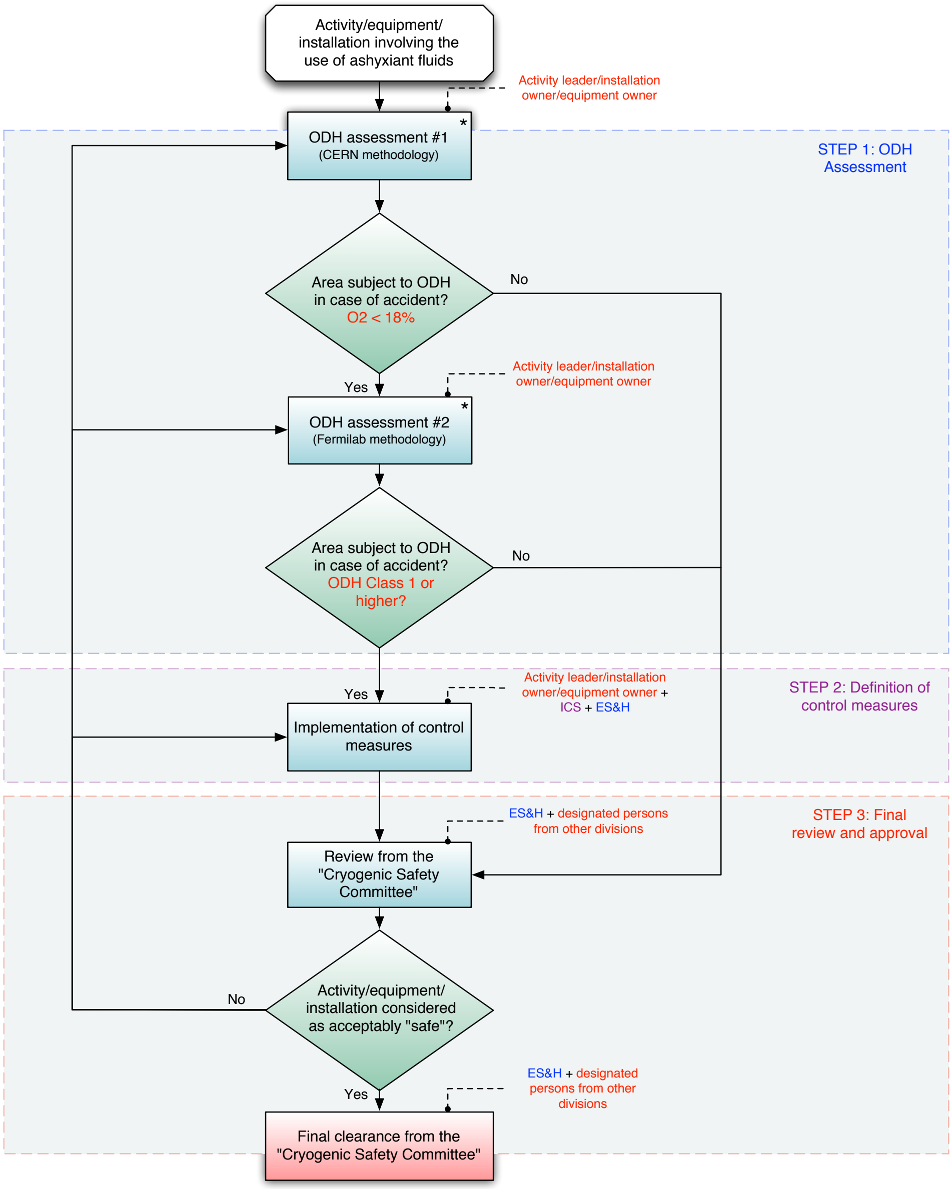
- ESS ODH Safety process & implementation - ESS-0038692 [2].

- AFS 2014:43 Chemical Hazards in the Working Environment.
- AFS 1997:7 Gases.
- EN 13458-3 - Static vacuum insulated vessels - Operational requirements [3].

5. MANAGING ODH-SITUATIONS

No use of asphyxiant cryogenic fluids or compressed gases is permitted at ESS without a formal evaluation of the ODH Class which shall be conducted through a specific ODH process for all activities which are physically capable of exposing individuals to an oxygen deficiency.

The ODH process can be divided into three main steps as shown in the following flowchart (Figure 1). Note that the process is built around quantitative assessment followed by independent expert review that will provide final clearance of the activity/area/equipment before operation.



* For specific and complex cases, further ODH analyses such as Computational Fluid Dynamics (CFD) might be necessary

Figure 1 - ESS ODH process

5.1. Step 1: ODH assessment

Any area at ESS known to have an oxygen concentration <18% (during normal and/or off-normal operation) is considered to be an oxygen deficient area. All areas intended for human occupancy at ESS shall have an environment or environmental controls that will normally ensure that the concentration of oxygen remains ≥18%.

If an area contains equipment or sources of inert gas that could lead to a significant decrease in oxygen concentration, additional measures shall be taken to reduce risk to personnel. The goals of an ODH assessment are to evaluate the risk level in a given area, to classify the area based upon the risk level, that is, to assign an ODH Class to the area, and to specify additional safety measures to be taken to reduce risks[1].

5.1.1. ODH assessment #1: Steady-state calculation model (CERN)

The purpose of the CERN's ODH assessment methodology [4] is to provide to any non-cryogenic expert with a fast and simple steady-state calculation model aiming at assessing the O_2 concentration remaining in the atmosphere of a specific area in case of a complete release of asphyxiant fluid without considering any ventilation rate, leak rate or time parameter.

5.1.1.1. ODH Assessment Equations

The O_2 concentration estimation in a confined volume is calculated using the following equation (Table 1):

Table 1 - ODH Assessment equation (CERN's model)

Formula	Definitions
$C = \frac{0,21(V - Vgas)}{V}$	C = oxygen concentration after the release [%]
	V = confined volume [m^3]
	V_{gas} = volume of gas discharged at room's temperature and pressure [m^3]

Remark: for large enclosure spaces such as experimental halls, ODH might not represent a direct threat for people safety considering an entire homogenous mixture. However, there could be some localized areas with oxygen depletion. Therefore, whenever applicable a smaller enclosure space could be considered for the ODH assessment.

5.1.1.2. ODH Class

The ODH assessment carried for every activity/area/installation involving the use of asphyxiant fluids allows determining an ODH Class that is calculated based on the selection of the "most credible scenario" defined with the help of the relevant experts.

The classification of the ODH Class as well as the associated actions are listed in the table below (Table 2):

Table 2 - ODH Class (CERN's model)

ODH Class	**O_2 concentration** in case of homogeneous mixture	Actions

[1] The classification of an area can change depending on the activities being performed. If conditions and/or activities change in ways that significantly increase the risk, the associated quantitative assessment must be accordingly revised.

0	$O_2 \geq 18$ %	Refer to control measures in 5.2.1[2]
"not safe"	$O_2 < 18$ %	A further ODH assessment shall be done according to the ODH process

5.1.2. ODH assessment #2: Dynamic calculation model (FERMILAB)

The purpose of the FERMILAB's ODH assessment methodology [4] is to provide to any non-cryogenic expert with a dynamic calculation model aiming at assessing the O_2 concentration remaining in the atmosphere of a specific area during and after an accidental release of asphyxiant fluid considering the ventilation rate, leak rate and time parameter.

5.1.2.1. ODH Assessment Equations

Oxygen concentration estimation, in a confined volume, during and after release of an inert gas can be calculated depending on the case, as follows (

Table 3):

Table 3 - ODH Assessment equation (FERMILAB's model)

#	Time	Mixing	Ventilation	Type	Diff. eq.	Concentration
A	During Release	Perfect mixing	Into confined volume		$V\frac{dC}{dt} = 0.21Q - (R+Q)C$	$C(t) = \left(\frac{0.21}{Q+R}\right)\left[Q + R\,e^{-\left(\frac{Q+R}{V}\right)t}\right]$
B	During Release	Perfect mixing	From confined volume	Ventilation rate greater than spill	$V\frac{dC}{dt} = 0.21(Q-R) - QC$	$C(t) = 0.21\left(1 - \frac{R}{Q}\left(1 - e^{-\frac{Q}{V}t}\right)\right)$
C	During Release	Perfect mixing	From confined volume	Ventilation rate less than spill	$V\frac{dC}{dt} = -R\,C$	$C(t) = 0.21\,e^{-\frac{R}{V}t}$
D	After Release	Perfect mixing			$V\frac{dC}{dt} = 0.21\,Q - Q\,C$	$C(t) = 0.21 - \left[0.21 - C_r(t_e)\right]e^{-\frac{Q}{V}(t-t_e)}$

Definitions:

C = oxygen concentration [%].
Cr = oxygen concentration during the release [%].
Ce = oxygen concentration after the release has ended [%].
Q = ventilation rate of fan(s) [m^3/s].

[2] According to the ODH process, depending of the complexity of the case the Cryogenic Safety Committee can require a further ODH analysis and additional control measures even if the situation has been initially assessed as "ODH Class 0", e.g whenever ventilation, leak rate, time parameter or confined volume configuration have an impact on the final ODH

R = spill rate into confined volume [m^3/s].
t = time [s] (beginning of release is at t=0).
t_e = time when release has ended [s].
V = confined volume [m^3].

5.1.2.2. ODH Class

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 activity, the fatality rate shall be determined on an activity-by-activity basis. For a given activity/area/equipment, 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. However, for the sake of simplification only the “most credible scenario” is considered for the ODH assessment of every activity/area/equipment involving the use of asphyxiant fluids. The oxygen deficiency hazard fatality rate is defined as follows:

Table 4 – ODH fatality rate (FERMILAB's model)

Formula	Definitions
$\phi = P_i F_i$	ϕ= the ODH fatality rate (per hour)
	Pi = the expected failure rate of the “most credible scenario” (per hour)
	Fi = the probability of a fatality due to “most credible scenario”

When possible, the value of P_i shall be determined by operating experience at ESS; otherwise data from similar systems elsewhere or other relevant values shall be used. Estimates of equipment failure rates are given in Appendix 8.1.

The value of F_i is the probability that a person will die if the “most credible scenario” 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 2).

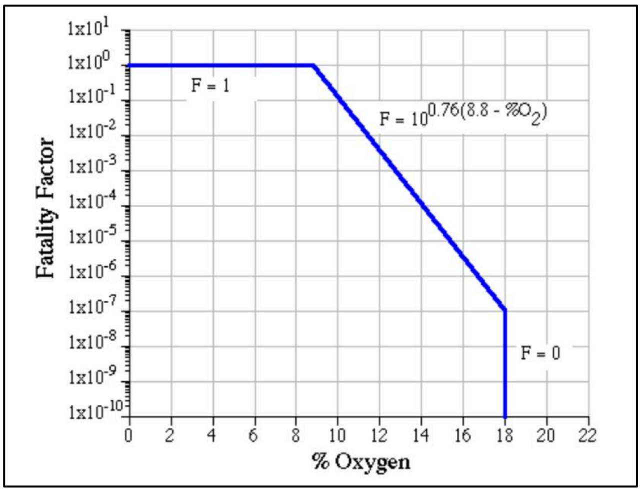


Figure 2: Fatality probability as a function of the lowest oxygen concentration (partial pressure)

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.

The classification of the ODH class depends on the ODH fatality rate as ϕ as shown in the table below (Table 5):

Table 5 - ODH Class (FERMILAB's model)

ODH Class	[ϕ] (hr^{-1})	Actions
0	$\leq 10^{-7}$	Refer to control measures in 5.2.1[3]
1	$>10^{-7}$ …but… $\leq 10^{-5}$	Refer to control measures in 5.2.1
2	$>10^{-5}$ …but… $\leq 10^{-3}$	Refer to control measures in 5.2.1
Forbidden area	$>10^{-3}$	No access to the area is allowed. Immediate control measures shall be implemented.

[3] According to the ODH process, depending of the complexity of the case the Cryogenic Safety Committee can require a further ODH analysis (e.g. Computation Fluid Dynamics) and/or additional control measures.

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

5.2. Step 2: Definition of control measures

Control measures appropriate to the ODH Class shall be implemented as stated in the ODH assessment and Technical Appendix.

ODH Class 0 is the least hazardous. ODH Class 2 is the most hazardous. The requirements mentioned in 5.2.1 are to be followed to control potential ODH events.

Equipment at ESS shall be designed and installed to ensure that areas intended for human entry during normal operation are not higher than ODH Class 2. No human access will be allowed in areas with an ODH Class higher than 2 unless control measures are implemented in order to reduce the ODH Class to an acceptable level, i.e. ODH Class 0, 1 or 2.

As far as possible, preventive and protective measures shall be implemented in a fashion that reduces the excess risk of fatality from exposure to an oxygen deficient atmosphere to no more than 10^{-7} per hour. In parallel of the ODH assessment, it is highly recommended to cover the following topics in a working group involving all the relevant stakeholders:

1 - Environmental Controls

- A – Ventilation - with Conventional Facilities Division
  - i) Forced
  - ii) Natural, including air makeup
- B – Monitoring - with Integrated Control System and Accelerator
  - i) Area oxygen monitoring
  - ii) Cryogenic systems

2 - Personnel Controls - with Environment Safety and Health Division

- A - Posting
- B - Entry control (locks, fencing, etc.)

3 - Emergency Procedures - with Environment Safety and Health Division

4 - Special Requirements - with Environment Safety and Health Division

- A - Self-rescue supplied atmospheric respirators (escape packs)
- B - Unusual procedures

5.2.1. ODH control measures requirements

Once the ODH assessment has been carried out, control measures shall be implemented according to the following list (Table 6):

Table 6 - ODH control measures requirements

ODH Class	0	1	2
Technical Safety measures			
Warning signs	X	X	X
Ventilation		*	*
Area (fixed) Oxygen Monitoring	*	X	X
Organizational Safety measures			
Medical approval as ODH qualified		*	*
ODH training (e-learning)	X	X	X
Personal oxygen monitor		X	X
Self-rescue mask		*	*
Presence of minimum 2 persons			X
Administrative Safety measures			
Access restricted to authorized personnel only		X	X
Emergency procedure		X	X
Operating procedure	X	X	X

* To be evaluated case by case with the help of ES&H

Remark: Note that the above-mentioned table is non-exhaustive and additional control measures can be required by the Cryogenic Safety Committee or ES&H for specific cases.

5.2.2. ODH Training

Individuals engaged in ODH class 0 or greater operations shall receive training in oxygen deficiency hazards and associated safety measures. The following topics should be covered.

1 – Introduction to activities at ESS involving Oxygen Deficiency

2 – Definition of Oxygen Deficiency Hazard

3 - Effects of Exposure to Reduced Atmospheric Oxygen

4 - ODH Safety awareness

A - Exposure Limit at ESS
B - ODH Classification Scheme
C - Required Control Measures
D – Emergency procedure and evacuation

Note that an ODH e-learning course will be soon available.

5.2.3. Emergency Evacuation and Rescue

The following flow chart (Figure 3) shows the process for conducting emergency evacuation and rescue. Under no circumstances shall staff enter or re-enter a space in which an ODH alarm is sounding. Entry under these conditions shall only be done by qualified rescue personnel such as the Fire Department.

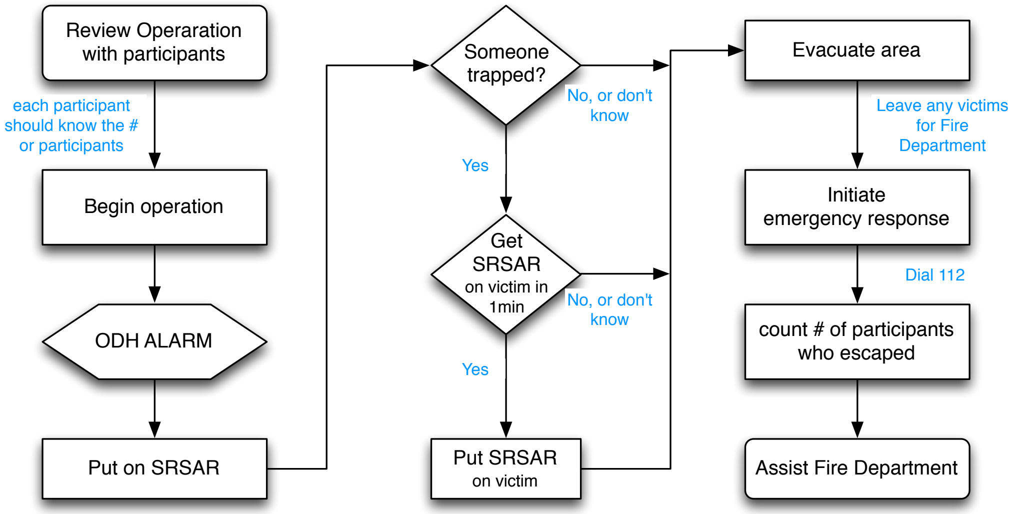


Figure 3: Emergency evacuation and rescue flowchart

Self Rescue Supplied Atmosphere Respirator (SRSAR) or escape pack

5.3. Step 3: Review and approval

Every ODH assessment carried out at ESS; independently from its results, shall be submitted to a Cryogenic Safety Committee for review and approval in order to address the following aspects:

- Validate the relevancy of the hazardous scenarios considered for the study.
- Validate the relevancy of the ODH calculation model chosen for the study.
- Validate the list of control measures foreseen to guaranty the safety of the activity/equipment/installation.
- Provide an official clearance for the start-up of the activity/equipment/installation.

6. ODH IMPLEMENTATION

6.1. Roles and responsibilities

The various roles and responsibilities of the main stakeholders in the implementation of the ODH process are defined as follows:

Activity leaders and equipment/area responsible: responsible for the ODH assessment and implementation of control measures related to their activity and equipment/area.

Operators: provide relevant information and knowledge to the ODH assessment regarding the activity/equipment/area to be analysed.

ES&H Division: provides help and support on the ODH process from the choice of the relevant methodology to be carried out for the ODH assessment to the implementation of control measures such as training and Personal Protective Equipment.

ICS Division: provide help and support for the implementation of ODH detection system.

Cryogenic Safety Committee (CSC): reviews and approves every activity/equipment/area involving the use of asphyxiant agents. The review and approval covers the ODH assessment, the selection of control measures as well as the content of the Safety documentation.

6.2. Safety documentation

Every activity leader and equipment/area responsible shall demonstrate the compliance of their activity/equipment/area involving the use of asphyxiant agent with applicable regulations and standards. For this purpose, they shall prepare and submit the following safety documentation to the Cryogenic Safety Committee as well as to ES&H for review and approval:

- ODH assessment including the list of control measures to be implemented.
- Emergency procedure in case of an ODH event.
- Material Safety Data Sheet (MSDS) of the fluids involved.
- Training records.

6.3. Contacts

Qualified persons can be contacted for advice and expertise on the following:

- Stuart Birch (stuart.birch@esss.se) – ODH detection system
- Nuno Elias (nuno.elias@esss.se) or Duy Phan (duy.phan@esss.se) - ODH assessment methodology
- Bertil Winér (bertil.winer@esss.se) - ODH control measures

6.4. Examples of case studies

Table 7 - ODH case studies at ESS

Activity/equipment/installation	Reference
Accelerator tunnel	https://ess-ics.atlassian.net/wiki/display/ASR/ODH+Assessment+Accelerator+Tunne
Utgård Laboratory	https://ess-ics.atlassian.net/wiki/display/ELFAS/ODH+Assessment+TBP+Laboratory

7. REFERENCE DOCUMENTS

[1] ESS Procedure for Systematic Work Environment Management, ESS 0051380

[2] N.Elias, "ODH Safety process & implementation," ESS-0038692 .

[3] "EN 13458-3 - Static vacuum insulated vessels - Operational requirements".

[4] D.Phan, "ODH Calculation tool," ESS-0043310.

8. APPENDIX

8.1. Equipment Failure rates estimates

System	Failure Mode	Failure Rate
Compressor (Two-stage Mycom)	Leak	5×10^{-6}/hr
	Component rupture	3×10^{-7}/hr
Dewar	Loss of vacuum	1×10^{-6}/hr
Electrical Power Failure (unplanned)	Time Rate	1×10^{-4}/hr
	Demand Rate	3×10^{-4}/D
	Time Off	1 hr
Fluid Line (Cryogenic)	Leak	5×10^{-7}/hr
	Rupture	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

System	Failure Mode	Failure Rate
U-Tube Change (Cryogen Release)	Small Event	3×10^{-2}/D
	Large Event	1×10^{-3}/D
Batteries, Power (UPC) supplies	No output	3×10^{-6}/hr
Circuit Breakers	Failure to operate	1×10^{-3}/D
	Premature Transfer	1×10^{-6}/hr
DIESEL (Complete plant)	Failure to start on demand	3×10^{-2}/D
(Emergency Run Loads)	Failure to run	3×10^{-3}/hr
(Engine Only)	Failure to run	3×10^{-4}/hr
ELECTRIC MOTORS	Failure to start on demand	3×10^{-4}/D
	Failure to run - normal	1×10^{-5}/hr
	Failure to run - extreme	1×10^{-3}/hr
FANS (fan, motor & starter)	Failure to run	9×10^{-6}/hr
FUSES	Premature open	1×10^{-6}/hr
	Failure to open	1×10^{-5}/D
FLANGES	Leak, 10 mm^2 opening	4×10^{-7}/hr
With reinforced & preformed gaskets	Rupture	1×10^{-9}/hr
FLANGES With packing or soft gaskets	Leak, 10 mm^2 opening	4×10^{-7}/hr
	Packing blowout	3×10^{-8}/hr
	Rupture	1×10^{-9}/hr
INSTRUMENTATION	Failure to Operate	1×10^{-6}/hr
(amplification, transducers, calibration, combination)	Shifts	3×10^{-5}/hr
MOTORIZED LOUVER	Failure in continuous operation	3×10^{-7}/hr
PIPING	Small leak 10 mm^2	1×10^{-9}/hr-m
	Large leak 1000 mm^2	1×10^{-10}/hr-m
	Rupture	3×10^{-11}/hr-m
PIPING WELD	Small leak 10 mm^2	2×10^{-11}(D/t)/hr-m
D = Diameter t = wall thickness	Large leak 1000 mm^2	2×10^{-12} (D/t)/hr-m
	Rupture	6×10^{-13} (D/t)/hr-m
PUMPS	Failure to start on demand	1×10^{-3}/D
	Failure to run - normal	3×10^{-5}/hr
	Failure to run - extreme	1×10^{-3}/hr
RELAYS	Failure to energize	1×10^{-4}/D
	Failure No contact to close	3×10^{-7}/hr
	Short	1×10^{-8}/hr
	Open NC contact	1×10^{-7}/hr
SOLID STATE Hi Pwr application	Fails to function	3×10^{-6}/hr
	Shorts	1×10^{-6}/hr
SOLID STATE Low Pwr application	Fails to function	1×10^{-6}/hr
	Shorts	1×10^{-7}/hr
SWITCHES	Limit: Fail to operate	3×10^{-4}/D
	Torque: Fail to operate	1×10^{-4}/D
	Pressure: Fail to operate	1×10^{-4}/D
	Manual: Fail to transmit	1×10^{-5}/D
	Contact shorts	1×10^{-8}/hr
TRANSFORMERS	Open contact	1×10^{-6}/hr
	Short contact	1×10^{-6}/hr
VALVES (motor operated)	Fails to Operate (plug)	1×10^{-3}/D

System	Failure Mode	Failure Rate
	Fails to remain open	1×10^{-4}/D
	External leak	1×10^{-8}/hr
	Rupture	5×10^{-10}/hr
VALVES (solenoid operated)	Fails to Operate	1×10^{-3}/D
VALVES (air operated)	Fails to Operate	3×10^{-4}/D
	Fails to remain open	1×10^{-4}/D
	External leak	1×10^{-8}/hr
	Rupture	5×10^{-10}/hr
VALVES (check)	Fails to Open	1×10^{-4}/D
	Reverse leak	3×10^{-7}/D
	External leak	1×10^{-8}/hr
	Rupture	5×10^{-10}/hr
VALVES (Orifices, flow meter)	Rupture	1×10^{-8}/D
VALVES (manual)	Fails to remain Open (plug)	1×10^{-4}/D
	External leak	1×10^{-8}/hr
	Rupture	5×10^{-10}/hr
VALVES (relief)	Fails to Open	1×10^{-5}/D
	Premature Open	1×10^{-5}/hr
VESSELS (pressure)	Small Leak, 10 mm^2	8×10^{-8}/hr
	Disruptive Failure	5×10^{-9}/hr
Wires	Open	3×10^{-6}/hr
	Short to GND	3×10^{-7}/hr
	Short to PWr	1×10^{-8}/hr

8.2. Human Error Rate estimates

Estimated error rate D^{-1}	ACTIVITY
1×10^{-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.
1×10^{-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.
1×10^{-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.
1×10^{-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.

9. DOCUMENT REVISION HISTORY

Version	Reason for revision	Date
1	First Revision	2016-04-14