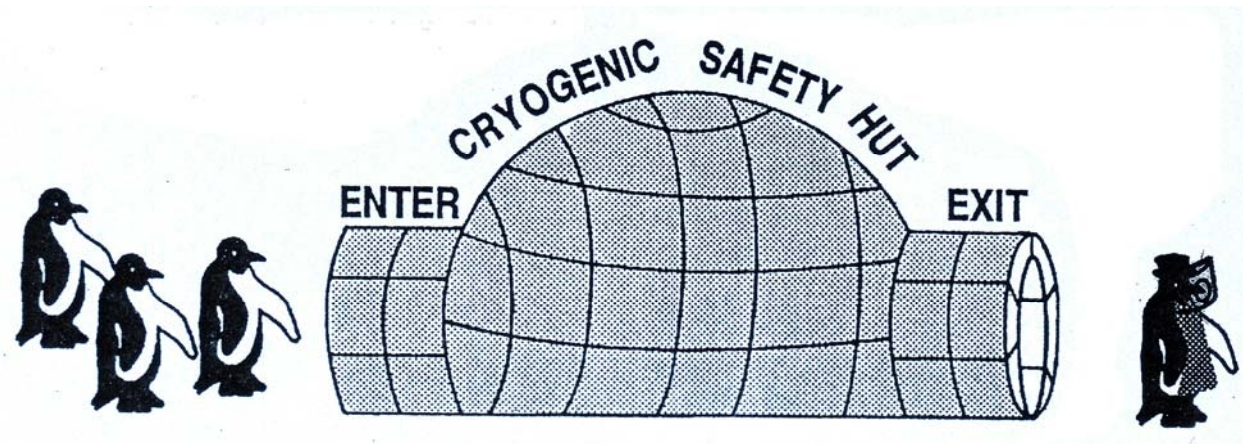
PHYSICS DIVISION CRYOGENIC SAFETY MANUAL



PREPARED BY
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PHYSICS DIVISION

CRYOGENIC SAFETY MANUAL

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1. INTRODUCTION

1.1 Physics Division Cryogenic Safety Committee Charter

Purpose

In keeping with the Physics Division policy to give the highest priority to Environmental, Safety, and Health concerns in its operations, it is the intent of Physics Division management to minimize cryogenic hazards to staff and visitors and to assure adherence to applicable safety codes. This will be accomplished through the development of operational procedures, the proper training of personnel, the design of equipment, and the establishment of a Cryogenic Safety Committee.

Responsibilities and Functions

- Develop the Physics Division Cryogenic Safety Manual
  - Define Physics Division Cryogenic Safety Policy and Requirements
  - Establish design criteria
- Establish the requirements and scope of cryogenic training of Physics employees and provide for training in specific tasks as needed.
- Review and approve requests for variance from the rules, regulations and procedures set forth in the Physics Division Cryogenic Safety Manual.
- Review the design and operation of existing and proposed cryogenic systems in the Division for adherence to regulatory requirements.
- Identify unsafe conditions and/or practices and assist in the development of corrective action plans.
- Review personnel accidents, near-misses, and recommend preventive measures.
- Document meetings, inspections, and other cryogenic-safety activities undertaken by the Committee.

Composition

The Physics Division Cryogenic Safety Committee shall consist of at least three Physics Division members appointed by the Division Director and a member from the ESH Division.

Members having expertise in cryogenics from other divisions may be appointed at the discretion of the Division Director.

The Divisional Safety Coordinator shall be a member of the Committee.

Ad hoc members will be invited to participate in safety reviews of specific cryogenic equipment or when membership expertise needs to be expanded.

Frequency of Meetings

This Committee will convene at least quarterly in order to fulfill its responsibilities and accomplish the mandates as specified in this Charter.

Amendment of the Charter

The Committee will review the terms of its charter on an annual basis and at other times as needed and make recommendations for change to the Director of the Physics Division.

Reporting

The Physics Division Cryogenic Safety Committee will report to the Physics Division Director.

Approvals

The Committee's membership must be approved by the Physics Division Director.

1.2 Definition and Scope:

Cryogenic temperatures are defined as those below 120 K (-153°C). The safety criteria established in this document apply to the cryogens in use in the Physics Division, namely liquid helium and nitrogen. Flammable fluids, such as hydrogen, and reactive liquids, such as oxygen and fluorine, are excluded. The use of flammable cryogens will require special approval procedures not outlined in this document.

1.3 Overview of Cryogenic Safety Hazards

The safety hazards associated with the use of cryogenic liquids (Appendix 1) can be categorized as follows:

1) *Cold contact burns*

   Liquid or low-temperature gas from any of the specified cryogenic substances will produce effects on the skin similar to a burn.

2) *Asphyxiation*

   Degrees of asphyxia will occur when the oxygen content of the working environment is less than 20.9% by volume. Effects from oxygen deficiency become noticeable at levels below ~18% and sudden death may occur at ~6% oxygen content by volume. This decrease in oxygen content can be caused by a failure/leak of the cryogenic vessel or transfer line and subsequent vaporization of the cryogen.

3) *Explosion - Pressure*

Heat flux into the cryogen from the environment will vaporize the liquid and potentially cause pressure buildup in cryogenic containment vessels and transfer lines. Adequate pressure relief must be provided to all parts of a system to permit this routine outgassing and prevent explosion.

4) *Explosion - Chemical*

Cryogenic fluids with a boiling point below that of liquid oxygen are able to condense oxygen from the atmosphere. Repeated replenishment of the system can thereby cause oxygen to accumulate as an unwanted contaminant. Similar oxygen enrichment may occur where condensed air accumulates on the exterior of cryogenic piping. Violent reactions, e.g. rapid combustion or explosion, may occur if the materials which make contact with the oxygen are combustible.

1.4 Staff and Administrative Responsibility

It is the responsibility of the experimenter in charge of an apparatus to ensure that the cryogenic safety hazards are reduced to as low a level as is reasonably achievable. This will entail (1) a safety analysis and review for all cryogenic facilities, as described in Section 3, (2) cryogenic safety and operational training for relevant personnel, (3) upkeep of appropriate maintenance and inspection schedules and records.

It is emphasized that it is the responsibility of the experimenter to maintain the system in the original working order, i.e. the condition in which the system was approved for use. Alterations to the system which impact worker safety must be reported to the Physics Division Safety Coordinator.

The ultimate responsibility for safety rests with the worker and is best ensured by thorough education and awareness

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2. REFERENCE MATERIAL

The regulatory and technical references listed below can be found in the Physics Division Office, in the Safety reference section.

2.1 Regulatory References

1. DOE 6430.1A - *General Design Criteria* - This Order covers specific requirements for cryogenic systems.

2. DOE 5481.1B - *Safety Analysis and Review System* - Makes no specific mention of cryogenic systems, but this Order is mandatory for application to cryogenic systems under the provisions of DOE Order 6430.1A, where, in paragraph 1574-5, the

following statement appears: "All cryogenic systems shall be subjected to a safety review in accordance with DOE 5481.1B".

3. DOE 5700.6C - *Quality Assurance* - Makes no specific mention of cryogenic systems, but the DOE Order on Quality Assurance is mandatory for application to cryogenic systems under the provisions of DOE Order 6430.1A, 1574-4.1.

4. CGA Pamphlet P-1 - *Safe Handling of Compressed Gases in Containers,* Compressed Gas Association, Incorporated, Arlington, Virginia. The applicable portions of these regulations are mandatory for <u>liquid helium and nitrogen</u> under paragraph 1574-3.1 of DOE Order 6430.1A. Written, unquestionably, in support of the transportation industry, but contains information of general applicability and within the scope of ATLAS operations. Paragraph 1574-3.1 is clearly not intended to address transportation issues, implying that this CGA pamphlet is to be applied in the DOE setting irrespective of the role, if any, played by transportation in the operations under consideration.

5. CGA Pamphlet S-1.1 - *Pressure Relief Device Standards Part 1* - Cylinders for Compressed Gases, Compressed Gas Association, Incorporated, Arlington, Virginia. Mandatory under paragraph 1574-2.9 of DOE Order 6430.1A. Applies to storage vessels of circular cross section designed for pressures higher than 40 psia and having a capacity of 454 kg water or less. Applies to <u>liquid helium and nitrogen</u> as well as to other cryogenic liquids. Basically for the designer but a close reading may yield some useful information to the person purchasing a storage vessel.

6. CGA Pamphlet S-1.2 - *Pressure Relief Device Standards Part 2* - Cargo and Portable Tanks for Compressed Gases, Compressed Gas Association, Incorporated, Arlington, Virginia. Mandatory under paragraph 1574-2.9 of DOE Order 6430.1.A. Applies to cargo tanks and portable tanks having a water capacity exceeding 454 kg. A "portable tank" is one that is attached to a motor vehicle or other vehicle.

7. CGA Pamphlet S-1.3 - *Pressure Relief Device Standards Part 3* - Compressed Gas Storage Containers, Compressed Gas Association, Incorporated, Arlington, Virginia. Mandatory under paragraph 1574-2.9 of DOE Order 6430.1.A. Applies to any permanently mounted storage container. Applies to <u>liquid helium and nitrogen</u> as well as to other cryogenic liquids. Basically for the designer but a close reading might provide useful information to the person purchasing a storage vessel.

8. ASME - *Boiler and Pressure Vessel Code* - Mandatory under DOE Order 5480.4. Is also indicated as mandatory in DOE Order 6430.1.A. The relevant portion of this document for cryogenic safety is Section VIII. The identification of this code document in Order 5480.4 implies that it is applicable in all settings within the DOE system including the arena of experimental equipment design and construction.

9. ASME B31.1 - *Power Piping* - Mandatory under paragraph 1574-2.8.1 of DOE Order 6430.1A for the design and inspection of welded joints.

10. ASME B31.3 - *Chemical Plant and Petroleum Refinery Piping* - Mandatory under DOE Order 6430.1A for the design and inspection of welded joints.

2.2 Regulatory References for Other Cryogenic Liquids

1. NFPA 50 - *Standard for Bulk Oxygen Systems at Consumer Sites* - National Fire Protection Association, Batterymarch Park, Quincy, Massachusetts. These regulations are mandatory through DOE Order 5480.4.

2. NFPA 50B - *Standard for Liquefied Hydrogen Systems at Consumer Sites* - National Fire Protection Association, Batterymarch Park, Quincy, Massachusetts. These regulations are mandatory through DOE Order 5480.4.

3. CGA Pamphlet G-4.1 - *Cleaning Equipment for Oxygen Service* - compressed Gas Association, Incorporated, Arlington, Virginia. Mandatory under paragraph 1574-4.2 of DOE Order 6430.1A.

4. NASA SP-3072 - *ASRDI OXYGEN TECHNOLOGY SURVEY Volume II: Cleaning Requirements, Procedures, and Verification Techniques* - Mandatory under paragraph 1574-4.2 of DOE Order 6430.1A.

5. MIL-STD-1330C(SH) - *Cleaning and Testing of Shipboard Oxygen, Nitrogen and Hydrogen Gas Piping Systems* - Mandatory under paragraph 1574-4.2 of DOE Order 6430.1A. This regulation refers to nitrogen only in the context of its use in the purging of oxygen and hydrogen lines and in the context of air separation oxygen-nitrogen plants. It therefore seems irrelevant to the <u>use</u> of liquid nitrogen in the Physics Division.

6. 29 CFR 1910.103© - *Liquefied Hydrogen Systems* - Mandatory under DOE Order 5480.4. An OSHA standard.

7. 29 CFR 1910.104 - *Oxygen* - Mandatory under DOE Order 5480.4. An OSHA standard.

2.3 Technical References for Cryogenic Technology

1. *Technology of Liquid Helium*, edited by R. H. Kropschot, B. W. Birmingham, and D. B. Mann, National Bureau of Standards Monograph 111 (1968). - A technical review which contains an extensive and thorough discussion of relief valve sizing for liquid helium vessels.

2. *Experimental Techniques in Low-temperature Physics,* G. K. White, 3rd Edition, Clarenden Press, Oxford (1979). - A useful source book for the design of small experimental systems using liquid helium.

3. *Cryogenic Technology,* edited by Robert W. Vance, John Wiley and Sons, Inc., New York (1963). - The chapter on heat transfer by J. A. Clark is clear and concise: a very good introduction.

4. *Roark's Formulas for Stress and Strain,* Warren C. Young, 6th Edition, McGraw-Hill Book Co., New York (1989). - A useful adjunct to Section VIII of the Pressure Vessel Code in evaluating safe working pressures for various structures.

5. *Heat Transfer at Low Temperatures,* edited by Walter Frost, Plenum Press, New York (1975). - A comprehensive treatment.

6. *Selected Cryogenic Data Notebook,* compiled and edited by J. E. Jensen, R. B. Stewart, and W. A. Tuttle, of the Bubble Chamber Group at Brookhaven National Laboratory (1962). - An invaluable compendium of the physical properties at low temperature for most commonly used materials and cryogens.

7. *Handbook on Materials for Superconducting Machinery,* MCIC-HB-04, Metals and Ceramics Information Center, Batelle, Columbus Laboratories. - Exhaustive compilation of the mechanical, thermal, electrical and magnetic properties of structural materials at cryogenic temperatures.

8. *Flow of Fluids through Valves, Fittings, and Pipe,* by the Engineering Division of Crane Co., 104 N. Chicago St., Joliet, IL, Copyright 1969.

3. PHYSICS DIVISION CRYOGENIC SAFETY POLICY AND REQUIREMENTS

In providing for cryogenic safety, hazards shall be considered as belonging to one of two classes:

1. Hazards with a potential for personal injury.

2. Hazards that pose a risk to equipment and/or operation which have no potential for personal injury.

Hazards of the first class shall be reduced to as low a level as is reasonably achievable. Hazards of the second class shall be reduced to as low a level as is cost-effective.

The existing DOE Order concerning cryogenic safety is Order 6430.1A Section 1574, which is primarily directed to liquefaction plants. This Order nonetheless applies to all cryogenic systems, including those discussed here. Section 1574 distinguishes two types of systems, namely, cryogenic storage vessels and cryogenic piping and fittings, with somewhat different rules and regulations for each class.

Some cryogenic experimental apparatus does not obviously fall into one class or the other. To clarify this situation, Physics Division policy in applying DOE Order 6430.1A shall be the following:

If a system involves the flow of cryogenic fluids through piping or subsystems contained in a vacuum chamber or vessel, the system shall be considered as a cryogenic storage vessel if the total volume of cryogenic fluid exceeds 12% of the volume of the surrounding vacuum vessel (even if the function of the apparatus is not cryogenic storage). If the cryogenic fluid volume is less than this amount, the system may be considered to be cryogenic piping and fittings.

3.1 Policy for New Cryogenic Equipment and Systems

The Physics Division policy is that new equipment and systems shall:

1. Meet all applicable federal and state requirements.

2. Be as safe as practicable.

3.2 Policy for Existing Equipment and Systems

It should be noted that for existing systems, the applicable federal and state requirements are, in many instances, those that existed at the time of procurement or construction of the system in question. The Physics Division policy for existing equipment and systems is that:

1. Existing equipment and systems shall meet all applicable federal and state requirements.

2. Existing equipment and systems must be as safe as practicable.

3. Existing equipment and systems shall be brought into compliance with current standards as far as is practicable. Safety aspects of any exception to current standards shall be reviewed in detail, and further operation shall be contingent on approval by the Division Director.

3.3 Physics Division Cryogenic Safety Analysis and Review Requirements

To insure and document compliance with division policy, all cryogenic equipment and systems shall be subject to a safety review by the Cryogenic Safety Committee.

3.3.1 Documentation Required for Safety Review

The following documents are required for a safety review of cryogenic equipment or systems:

1. A description of the system, which shall include the following:

   A. Schematics and flow diagrams as required to provide a complete and accurate functional description of the system.

B. Sufficient information to show that the components, materials, and construction techniques used are appropriate.

C. Parts lists with manufacturer's specifications as appropriate; e.g. pressure ratings for vessels and plumbing, flow capacity and cracking pressure for relief valves, etc.

D. Specification of other, connected systems as may be required for safety analysis.

2. A description of operating procedures, and of any necessary operator training. The following elements shall be included:

   A. A list of all valves and ports which have the potential of discharging cold gas or cryogens to atmosphere (The possibility of such a discharge causing personal injury should be evaluated).

   B. All required system maintenance in any way impacting safety shall be detailed (e.g. periodic inspection of pressure relief devices).

   C. Emergency procedures, including methods of evaluating and mitigating any oxygen deficiency hazard.

3. A safety analysis detailing the consequences of all significant possible component failures or operator errors. This shall include:

   A. A listing of all hazards and the steps taken to mitigate them.

   B. An analysis demonstrating the adequacy of pressure relief valve sizing under worst-case failure conditions.

   C. Oxygen deficiency hazard (ODH) analysis evaluating the class of risk presented under worst-case failure conditions. Any level of risk higher than Class 0 (refer to Appendix 3) requires that special precaution (refer to Appendix 3 also) will be necessary.

4. METHODS OF COMPLIANCE

4.1 Vendor-Supplied System and Equipment

In the case of vendor-supplied systems and equipment, vendors shall provide documentation needed:

1. To demonstrate compliance with the safety criteria.

2. To provide information required to complete a safety analysis of the system or component in final, installed configuration, and to estimate interaction with any connected systems.

4.2 Relief Valve Sizing

Pressure relief valves must be installed on all vessels and piping which contain cryogenic fluids or might under some failure conditions contain cryogenic fluids (e.g. cryostat vacuum vessels). Note that current standards require pressure relief devices to be ASME code-certified.
Several steps are involved in determining flow requirements for relief valves:

1. Establish the maximum safe working pressure (MSWP) for all piping and vessels that may contain cryogenic fluids. Note that current standards require that any cryogenic storage vessel be designed by the rules of Section VIII of the ASME Pressure Vessel Code.

2. Determine the maximum rate of efflux of the contained cryogenic fluid required to maintain pressure below the MSWP in a worst-case failure scenario. Failure scenarios might include:

    a. Failure of a cryostat insulating vacuum to atmosphere.

    b. Failure of a cryostat insulating vacuum to the contained cryogen.

    c. Flow of cryogen from a connected system due to a valve failure or operator error.

    d. Trapping of cryogenic fluid due to valve failure or operator error.

3. Show that the relief valves, as actually installed, provide sufficient relief capacity. For high flow rates, the pressure drop in any plumbing leading to the relief valves may need to be considered. Flow capacity should be estimated for the particular gas involved, at the appropriate temperature and pressure.

5. OPERATIONAL REQUIREMENTS

5.1 Training of Cryogenic Personnel

All personnel working with cryogenic fluids must be thoroughly familiar with the hazards involved. They must also be familiar with all emergency measures that might be required in the event of an accident. Employees who have not worked with cryogenic fluids and systems must be trained on the job by experienced employees until thoroughly familiar with safe methods of operation.

The training will address:

- The physical, chemical and physiological hazards associated with cryogenic fluids

- The proper handling procedures for cryogens and cryogenic containers

- The emergency procedures required in case of an accident
- The reporting procedures in case of an accident

Additionally, each employee will receive training by the responsible scientist on the specific cryogenic equipment or system he is expected to use. This will cover:

- Description of the equipment
- Operating procedures
- Maintenance schedule and procedures
- Specific hazards
- Reporting of incidents

The training shall be documented. The documentation shall include: 1) content of training, 2) date, 3) name of trainer, 4) a dated training attendance list showing names of the trainees (typed or printed) and their signatures.

5.1.1 Cryogen Handling

The hazards associated with the handling of cryogenic fluids include:

- Cold contact burns and freezing (contact with cold liquid, gas or surface)

  The potential for freezing by contact with the extreme cold of cryogens necessitates varying degrees of eye, hand and body protection. When a cryogenic fluid is spilled on a person, a thin gaseous layer apparently forms next to the skin. This layer protects tissue from freezing, provided the contact with the cryogen involves small quantities of liquid and brief exposures to dry skin. However, having moist skin, exposure to moving cryogens, or extended periods of time, can freeze tissue.

  The most likely cause of frostbite to the hands and body is contact with cold metal surfaces. Since there is no protective layer of gas formed, frostbite will occur almost instantaneously, especially when the skin is moist.

  The damage from this freezing (frostbite) occurs as the tissue thaws. Intense hypothermia (abnormal accumulation of blood) usually takes place. Additionally, a blood clot may form along with the accumulation of body fluids, which decreases the local circulation of blood.

  Adequate protection and clothing is required at all times when handling, transferring or operating near cryogenic fluids (see 5.1.2).

- Asphyxiation (displacement of oxygen by inert gas)

  When liquid cryogens are expelled into the atmosphere at room temperature, they evaporate and expand on the order of 700 to 800 times their liquid volume. Even small amounts of liquid can displace large amounts of oxygen gas and decrease the oxygen content of the atmosphere below a safe level with a possibility of asphyxiation.

  Whenever possible, handling of cryogenic fluids where release into the atmosphere is possible should be done in open, well ventilated areas.

  When there is the possibility of an oxygen deficiency hazard (ODH) with a level of risk greater than Class 0, (see Appendix 3) oxygen monitors will be installed. If such a monitor triggers an ODH alarm, personnel are to leave the area immediately.

- Explosion (excessive buildup of pressure in container of cryogenic fluid)

  Heat flux into the cryogen is unavoidable regardless of the quality of the insulation provided. Since cryogenic fluids have small latent heats and expand 700 to 800 times to room temperature, even a small heat input can create large pressure increases.

  Dewars must be moved carefully. Sloshing liquid into warmer regions of the container can cause sharp pressure rises.

  Pressure relief devices must be provided on each and every part of a cryogenic system. Satisfactory operation of these devices must be checked periodically and may not be defeated or modified at any time.

  Vents must be protected against icing and plugging. When all vents are closed, enough gas can boil off in a short time to cause an explosion. Vents must be maintained open at all times.

  Liquid helium is cold enough to solidify atmospheric air. Only helium should be introduced or allowed to enter the helium volume of a liquid helium dewar. Precautions should be taken to prevent air from back-diffusing into the helium volume.

  Some materials may become brittle at low temperature and fail in the case of overpressure or mechanical shock. Only suitable materials may be used to store or transfer liquid cryogens.

- Fire/explosion (condensation of liquid oxygen)

  Liquid oxygen liquifies at a higher temperature than liquid helium or nitrogen. Consequently, liquid oxygen can condense on the exterior of cryogenic containers or transfer lines. An explosive situation may result if this oxygen-rich liquid is allowed to soak insulating or other materials which are not compatible with oxygen.

  Some oils can form an explosive mixture when combined with liquid oxygen. Surfaces where there exists a possibility of liquid oxygen condensation must be thoroughly cleaned and degreased.

5.1.2 Protective Clothing

Whenever handling or transfer of cryogenic fluids might result in exposure to the cold liquid, boil-off gas, or surface, protective clothing shall be worn. This will include:

- face shield or safety goggles
- safety gloves
- long-sleeved shirts, lab coats, aprons.

Eye protection is required at all times when working with cryogenic fluids. When pouring a cryogen, working with a wide mouth dewar or around the exhaust of cold boil-off gas, use of a full face shield is recommended.

Hand protection is required to guard against the hazard of touching cold surfaces. Loose insulating gloves can be used.

5.2 Maintenance and Inspection

Cryogenic systems and equipment must be inspected and maintained on a regular basis by qualified personnel to ensure safety. The schedule and nature of the maintenance must be included in the operating procedures manual. The inspection and maintenance shall be documented.

Every cryogenic system or equipment shall be inspected by qualified personnel before being put into operation for the first time or after modification. Inspection by qualified personnel shall also take place after an unusual incident which might affect the integrity and safety of a piece of cryogenic equipment.

One should note that these requirements for inspection, maintenance, calibration and documentation extend to the monitoring systems for oxygen deficiency.

5.3 Lockout-Tagout Procedure

The Lockout/Tagout Policy establishes basic requirements involved in locking and/or tagging out equipment while installation, maintenance, testing, repair or construction operations are in progress. The primary purpose is to prevent hazardous exposure to personnel and possible equipment damage. The procedures shall apply to the shutdown of all potential energy sources associated with the equipment. These could include pressures, flows of fluids and gases, electrical power, and radiation.

The formal lockout/tagout procedure for the Physics Division has been written and is the responsibility of the Physics Division Electrical Safety Committee. It is included as Appendix A of the Physics Division Electrical Safety Policy and Manual. The ANL-E lockout/tagout policy and procedure is included in the ESH Manual. The Physics Division procedure conforms to the ANL-E policy and procedure.

All personnel who are involved in the installation, maintenance, testing repair, or construction of cryogenic equipment in which there are energy sources associated with the equipment must undergo documented training in the use of the Physics Lockout/Tagout procedure.

5.4 Emergency Procedures

In case of emergency, e.g. explosion of a dewar, leave the area immediately and dial 911.

APPENDIX 1

Physical Properties of Cryogenic Liquids

Properties	He	H_2	Ne	N_2	Ar	O_2	CO_2
Boiling point (1 atm), K	4.2	20.3	27.1	77.3	87.3	90.2	194.7†
Critical temperature, K	5.2	33.0	44.4	126.3	150.9	154.8	304.2
Critical pressure, atm	2.2	12.8	26.2	33.5	48.3	50.1	72.8
Liquid density, g/ℓ	125	71	1206	808	1402	1410	1560*
Gas density (300 K), g/ℓ	0.16	0.082	0.82	1.14	1.63	1.3	2.0
Gas/Liquid expansion ratio at STP (V_g/V_ℓ)	780	865	1470	710	860	875	790

†Sublimation Point
*Solid at 1 atm

APPENDIX 2: Relief Valve Sizing for Cryogenic Systems

1.0 Introduction

Within a cryogenic system, adequate relief valves must be installed for all vacuum and cryogenic vessels, and also for any cryogenic lines that have the potential to trap cryogenic fluids.

Relief valves must be sized so that under worst-case failure conditions, the maximum pressure reached in any vessel is below the maximum safe working pressure (MSWP) for the vessel. No fixed prescription can be given to determine valve sizing for all, or even most cases. Each system must be analyzed in detail to properly determine worst-case failure modes and the required relief valve sizing.

Such analysis should proceed through several steps, which are discussed in general terms below. It should be noted that the following discussion is intended as a brief introductory guide, and in no way should be considered a comprehensive or complete treatment.

2.0 Vessel Pressure Ratings

The MSWP must be determined and documented for each vessel and piping element of the system. This includes both vacuum and cryogenic vessels, and also, both cryogenic piping and vacuum housing for any vacuum-insulated transfer lines.

In addition, for any vessel serving as a cryogenic storage vessel, DOE Order 6430.1A requires the vessel to be designed in accordance with Section VIII of the ASME Pressure Vessel Code. The following are some possible methods of determining the MSWP:

A. Documented manufacturer's pressure rating. One could use either MSWP, if provided, or 25% of the minimum yield or burst pressure.

B. Results of a pressure test, preferably hydrostatic, performed and documented by persons competent to perform pressure vessel tests in accordance with laboratory safety requirements, and in accordance with the requirements of Section VIII of the ASME Pressure Vessel Code.

C. Results of a detailed and documented stress analysis of all elements of a vessel, using a maximum allowable stress of 25% of the yield stress of the materials employed. Such a stress analysis might be a result of a numerical finite-element approximation or of a conservative application of the various formulas detailed in ref. [4] (references are contained in Section 2.3 Technical References for Cryogenic Technology).

3.0 Determining Worst-Case Failure Modes

For each volume requiring a relief valve, a credible worst-case failure mode must be determined. Generally, one should consider for a given failure mode only a single initiating failure (of either a procedure or a component), together with any subsequent failure or chair of failures that would naturally result from the initial failure. The following are examples of failure modes that should be considered:

A. An operator improperly opening or closing any given valve. This might result, for instance, in liquid nitrogen then being trapped in a section of transfer line, or in air being introduced into a cryogenic insulating vacuum.

B. Failure of a cryogenic vacuum vessel to air.

C. Failure of a vessel containing cryogenic liquid into the insulating vacuum vessel.

D. Failure of the inner, cryogenic tube of a transfer line.

E. Failure of the outer, vacuum housing of a transfer line.

In case A, above, the effects of opening valves to or from any connecting systems, such as gas storage or refrigerator, should also be considered.

For relief valve sizing, the worst-case failure mode is that failure mode resulting in the most rapid boil off of cryogenic fluid. With the exception of failure modes that cause the injection of cryogenic fluid from an outside system, the boil off will be determined by the heat-leak caused by the given failure mode.

3.1 Some Heat Transfer Processes

Determination of the heat leak due to a given failure requires detailed analysis of the particular system. The general methods for several cases are outlined below.

3.11 Condensation of Air on Vessels Containing Liquid Helium

For a bare (not wrapped in superinsulation) cryogenic vessel containing liquid helium, the worst-case failure mode is likely to be failure of the insulating vacuum to air. All the constituent gases of air will condense directly on the surface of the helium containing vessel; from reference [1], p. 270, such condensation produces a heat input of 1 to 6 watts/cm^2. For the ATLAS cryostats, an experiment was performed to determine the precise number, which turned out to be 1.4 watts/cm^2. In the absence of such experimental data, the most pessimistic value, 6 watts/cm^2 should be assumed. The heat leak due to air condensation for vessels which are wrapped in superinsulation is also detailed in reference [1].

3.12 Convective and Conductive Heat Transfer

In many cases the worst-case failure mode will be failure of an insulating vacuum to air, nitrogen, or helium with the heat transfer mechanism then being convection, or in the case of substantial amounts of superinsulation or other filler conduction, from the outer vacuum wall of the vessel to the inner vessel or piping containing the cryogenic fluid. The thermal conductivity of several gases is described in Reference [6].

Convective heat transfer is described in reference [3]. Appendix 2a to this gives estimates of the convective heat transfer values for several gases and temperatures.

4.0 Determining Boiloff Rates

Once the heat input to the cryogenic substance is known, the maximum rate of efflux must be determined.

In many cases the efflux results from simple boiling of a cryogenic fluid, and the rate can be simply estimated from the heat of vaporization of the cryogenic liquid.

In general, the efflux must be calculated by equating the enthalpy released by venting a portion of the cryogen (at the relief pressure) to the worst-case heat input. This may or may not be a simple matter, depending on the conditions that apply. Reference [1] contains a thorough discussion of such calculations for helium

5.0 Determining Pressure Drop from Venting Vessel to Atmosphere

For most vent lines and valves, the pressure drop will be dominated by the so-called minor loss term, which is approximately

$$\Delta p = 1/2 G^2 / \rho \qquad (1)$$

where G is the mass flow per unit cross-sectional area in grams/ (sec * cm^2), and ρ is the gas density at the exit of the element considered. Each bend or orifice in the flow path that causes substantial turbulence will add a term roughly given by expression (1) to the total pressure drop. Reference [8] details the pressure drops expected for various geometries of bends and orifices.

Expression (1) shows that for a given pressure drop, the flow through any system, such as a relief value, will scale as G^2/ρ. Since manufacturer's specifications usually give capacity for air at room temperature, this scaling relationship provides a means of estimating capacity of a given valve for various gases at cryogenic temperatures, such as nitrogen at 77 K or helium at 5 K.

Appendix 2b shows some examples of pressure drop estimates.

APPENDIX 2a

CONVECTIVE HEAT TRANSFER

The convective heat transfer coefficient, h_c, is given by (from Heat Transmission, W. H. McAdams, McGraw-Hill, NY (1942) pp 242-245):

$$\frac{h_c L}{k_f} = \frac{1}{2}\left[\left(\frac{L^3\ \rho_f^2\ g\Delta T}{\mu_f^2 T_f}\right)\left(\frac{C_p \mu_f}{k_f}\right)\right]^{0.25}$$

or

Watt/cm^2 K

$$h_c = \frac{1}{2}\left[\frac{k_f^3 \rho_f^2 g C_p}{\mu_f T_f}\right]^{0.25}\left(\frac{\Delta T}{L}\right)^{0.25} \qquad (1)$$

where k = thermal conductivity, ρ = density, C_p = specific heat, μ = viscosity, g = gravitational acceleration. Note that CGS units are used.

The subscript f means the quantities are to be evaluated at the "gas film" temperature, the arithmetic means of the temperature at the surface of the solid, and the temperature of the bulk of the gas.

The quantity L is the characteristic dimension of the system: e.g. diameter of a cylinder, spacing of parallel plates, or the edge length of a plane square. Equation (1) is valid so long as

$$\chi = \left[\frac{L^3\ \rho_f^2\ g\Delta T c_p}{\mu_f T_f k_f}\right] > 10^3$$

The actual heat flow Q is given by:

$$Q = h_c\ \Delta T \text{ Watts/cm}^2$$

We evaluate expression (1) for several gases and conditions (using CGS units):

I. Nitrogen at 293 K and 1 ATM

$k_f = 2.5\text{x}10^{-4}$ w/cm K, $\rho f = 1.16\text{x}10^{-3}$, $C_p = 1.04$ J/gm K, and $\mu f = 17.4\text{x}10^{-6}$ poise, so that

$$h_c = \frac{1}{2}\left[\frac{(2.51x10^{-4})^3(1.16\bullet 10^3)^2 x\, 980\, x\, 1.04}{174x10^{-6}\; x193}\right]^{1/4}\left(\frac{\Delta T}{L}\right)^{1/4}$$

$$= 4.04\text{x}10^{-4}\left(\frac{\Delta T}{L}\right)\ \text{Watt/cm}^2\,\text{K}$$

II. Nitrogen from 77 K to 293 K (T_f = 185 K, ΔT = 216 K) $k_f = 1.8\text{x}10^{-4}$ W/cm K, ρ_f = $1.84\text{x}10^{-3}$, $\mu_f = 121\text{x}10^{-6}$

and

$$h_c = \frac{1}{2}\left[\frac{(1.8\bullet 10^{-4})^3(1.84\bullet 10^{-3})^2 x\, 980\, x\, 1.04}{121x10^{-6}\; x185}\right]^{1/4}\left(\frac{\Delta T}{L}\right)^{1/2}$$

$$= 4.89\text{x}10^{-4}\left(\frac{\Delta T}{L}\right)^{1/4}\ \text{Watt/cm}^2\,\text{K}$$

III. Helium from 15 K to 293 K (T_f = 154, ΔT = 278) $k_f = 9.9\text{x}10^{-4}$ W/cm K, $\rho_f = 3.17\text{x}10^{-4}$, C_p = 5.5 J/gm K, $\mu_f = 131\text{x}10^{-6}$ poise, so that

$$h_c = \frac{1}{2}\left[\frac{(9.9x10^{-4})^3(3.17x10^{-4})^2 x\, 980\, x\, 5.5}{131x10^{-6}\; x154}\right]^{1/4}\left(\frac{\Delta T}{L}\right)^{1/4}$$

$$= 1.13\ \text{x}10^{-3}\left(\frac{\Delta T}{L}\right)^{1/4}\ \text{Watt/cm}^2\,\text{K}$$

IV. Helium from 15 K to 77 K (T_f = 46 K, ΔT = 26 K) $k_f = 4.52\text{x}10^{-4}$ W/cm K, $\rho_f = 1.06\text{x}10^{-3}$, $\mu_f = 60\text{x}10^{-6}$ poise, thus

$$h_c = \frac{1}{2}\left[\frac{(4.52\bullet 10^{-4})^3(1.06\bullet 10^{-3})^2 x\, 980\, x\, 5.5}{60\bullet 10^{-6}\bullet 46}\right]^{1/4}\left(\frac{\Delta T}{L}\right)^{1/4}$$

$$= 1.89\text{x}10^{-3} \left(\frac{\Delta T}{L}\right)^{1/4} \quad \text{Watt/cm}^2\,\text{K}$$

V. Helium from 77 K to 293 K (T_f = 185, ΔT = 216) $k_f = 1.11\text{x}10^{-3}$ W/cm K, $\rho f = 2.64\text{x}10^{-4}$,

C_p = 5.5 J/gm K, $\mu f = 148\text{x}10^{-6}$ poise

$$h_c = \frac{1}{2}\left[\frac{(1.11\text{x}10^{-3})^3(2.64 \bullet 10^{-4})^2 \text{x}\, 980\, \text{x}\, 5.5}{148\text{x}10^{-6}\, \text{x}\, 185}\right]^{1/4} \left(\frac{\Delta T}{L}\right)^{1/4}$$

$$= 1.04\text{x}10^{-3} \left(\frac{\Delta T}{L}\right)^{1/4} \quad \text{Watt/cm}^2\,\text{K}$$

APPENDIX 2b

RELIEF VENT PRESSURE DROPS

We calculate the pressure drops caused by the flow of gas through tubes and orifices using (CGS units) the following:

Define

G = mass flow (grams/(sec.cm^2))

ρ = density (g/cm^3)

η = viscosity (poise)

For flow through a tube or channel

$$\Delta P = \varphi \ell G^2 / (2\rho D_n) \qquad (1)$$

where

$$D_n = \text{effective diameter} = 4 \text{ x } \frac{\text{cross section area}}{\text{section total perimeter}}$$

ℓ = length of tube

and

$\psi = 0.326\ (GD_n/\eta)^{-0.25}$ (turbulent flow)

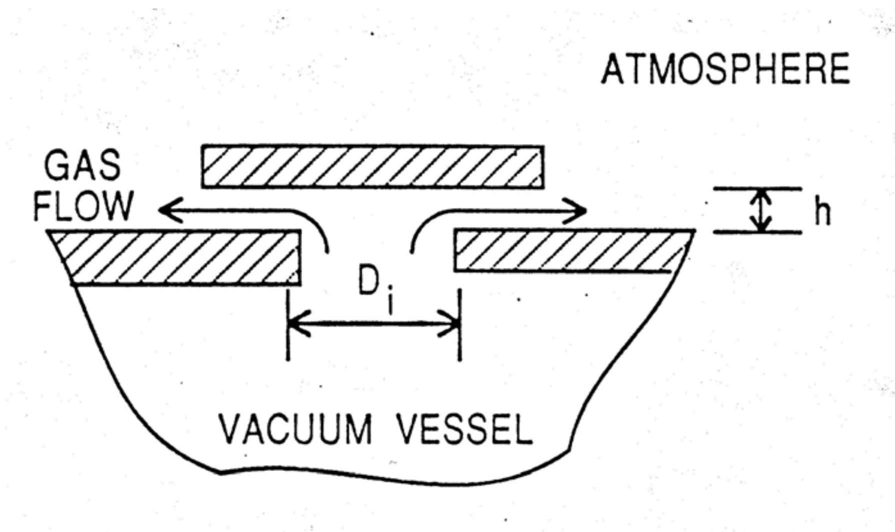
We also include a "minor loss" term

$$\Delta P = \frac{1}{2}\frac{G^2}{\rho} \qquad (2)$$

for the pressure drop occurring at any orifice or sharp bend in the flow channel. For most relief path geometries term (2) will be larger than term (1). Application of expression (2) is not always straightforward, a number of examples are discussed in ref. [8]. In what follows we assume the density of helium to scale according to the ideal gas law.

Example I. Vacuum Vessel Relief Vents

These are of the form



We treat this as an orifice with area = the lesser of ($\pi D_i h$) or ($\pi D_1^2/4$) and we take the pressure drop to be given by (2). We calculate the flow of helium gas through these vents for a pressure drop equal to the cracking pressure P_c plus one PSI. Under these conditions, the dimensions are:

	Unit	P_c	D_i	h	Area
A.	ATLAS Linac	1.1 psi	15.24 cm	2.5 cm	121.6 cm^2
B.	Rebuncher	3 psi	5.08	0.64	10.2
C	PII*	1 psi	15.24	2.5	121.6 cm^2

*for PII the overpressure = 2 psi

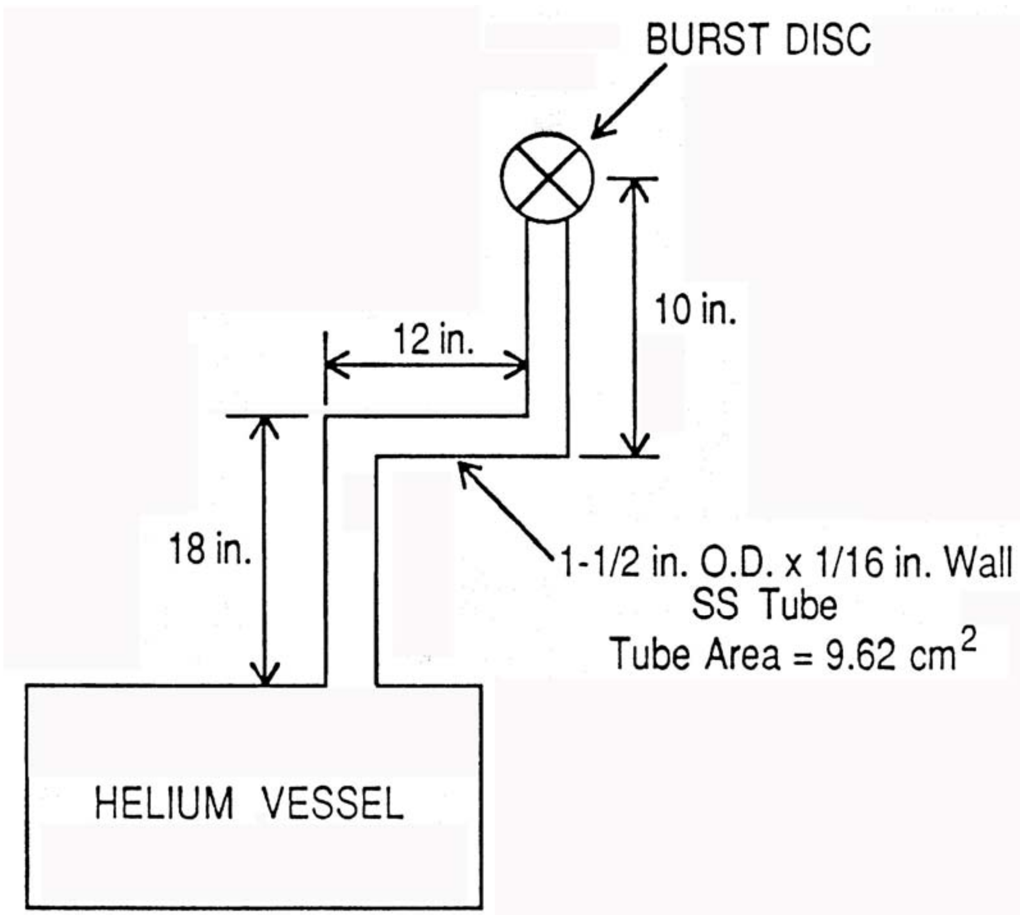
We assume (conservatively) that

$$\rho_{He} = \frac{4.857 \times 10^{-2}}{T} \, g/cc \qquad \text{(ideal gas) at 1 ATM.}$$

For ATLAS: He at 15.1 K, ΔP = 2 psi, Vent Area = 121.6 cm^2

Using $\Delta P = \frac{1}{2}\frac{G^2}{\rho}$ (1 psi = 6.9 x 10^4 dyne/cm^2)
then G = 29.2 g/cm^2 sec
thus Vent Capacity = 29.9 x 121.6 = 3630 g/s

Example II. Helium Vessel Vent – Rebuncher



We assume helium gas at 5 K, the dominant term is the "minor loss" term we take

$$\Delta P = \frac{1}{2}\frac{G^2}{\rho}$$

at each 90º bend, and at the outlet orifice – working backward from the outlet, and assuming $\rho = 9.8 \times 10^{-3}$ P (g/cc) where P is in atmosphere (ideal gas density), for a total flow of 420 g/sec, G = 420/9.62 = 43.7 g/sec cm^2

Location	Exit Pressure	Density	ΔP
Outlet	15 pisa	9.8×10^{-3}	1.4 psi
2nd bend	16.4	1.07×10^{-2}	1.3
1st bend	17.7	1.16×10^{-2}	1.2

We note that the frictional loss gives $\Delta P_1 = 0.2$ psi for this case, and

$$\Delta P_{Total} = 4.1 \text{ psi}$$

APPENDIX 3

Oxygen Deficiency Hazards (ODH)
(Taken largely from CEBAF Cryogenic Safety Manual)

Definitions

Oxygen Deficiency – the condition of the partial pressure of atmospheric oxygen being less that 135 mmHg (about 18% by volume at a barometric pressure of 740 mmHg at ANL). [American Conference of Governmental Industrial Hygienists]

Procedures

1. A quantitative assessment of the increased risk of fatality from (potential) 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 specify the Oxygen Deficiency Hazard Class as well as any unusual precautionary requirements.

2. Precautionary 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 greatest precautions.

Effects of Exposure to Reduced Atmospheric Oxygen

Air normally contains about 21%[1] oxygen with the remainder consisting mostly of nitrogen. Individuals exposed to reduced-oxygen atmospheres may suffer a variety of harmless effects. Table I 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 generally 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.

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.

[1]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.

TABLE I.
Effect Thresholds for Exposure to Reduced Oxygen
(Healthy Individuals at Sea Level)

Volume % Oxygen	Effect
17	Night vision reduced
	Increased breathing volume
	Accelerated heartbeat
16	Dizziness
	Reaction time 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	Spasmatic breathing
	Convulsive movements
	Death in 5-8 minutes

ODH Risk Assessment

The goal of ODH risk assessment is to estimate the rate at which fatalities will occur as a result of exposure to reduced-oxygen atmospheres.

Since the level of risk is tied to the nature of the operation, the fatality rate shall be determined on an operation-by-operation basis. For the given operation several events may cause an oxygen deficiency. Each even has an expected rate of occurrence and each occurrence has an expected probability of killing someone. The oxygen deficiency hazard fatality is defined as:

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

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 by operating experience at ANL; otherwise, data from similar systems elsewhere or other relevant values shall be used.

Estimates of "spontaneous" equipment failures rates are given in Tables II and III. The former contains median estimates collected from past ODH risk assessments at Fermilab. The latter contains values derived from the nuclear power industry.

General human error rate estimates are presented in Table IV. Table V lists conservative estimates of the rate of human error as a function of task type and time limit.

TABLE II
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 (Time Off)	1×10^{-4}/hr (1 hr)
Fluid Line (Cryogenic)	Leak or Rupture	3×10^{-6}/hr
Magnet (Cryogenic)	Leak or Rupture	1×10^{-6}/hr
U-Tube Change Release (Cryogenic)	Small Event Large Event	1×10^{-3}/hr 4×10^{-5}/hr

TABLE III

NRC EQUIPMENT FAILURE RATE ESTIMATES

FAILURE MODE		MEDIAN FAILURE RATE
Batteries Power 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	3×10^{-2} /D
(emergency loads)	Od: Failure to Run	3×10^{-3} / hr
Diesel (engine only)	Failure to Run	3×10^{-4} / hr
ELECTRIC MOTORS	Failure to Start	3×10^{-4} / hr
	Failure to Run	1×10^{-5} / hr
	Failure to Run (Extreme ENVIR)	1×10^{-3} / hr
FUSES	Premature, Open	1×10^{-6} / hr
	Failure to Open	1×10^{-5} /D
Gaskets	Leak	3×10^{-6} / hr
Flanges, Closures, Elbows	Leak/Rupture	3×10^{-7} / hr
Instrumentation (Amplification, Annunciators, Transducers, Calibration, Combination)	Failure to Operate	1×10^{-6} / hr
	Shifts	3×10^{-5} / hr
Pipes>3" High Quality	Rupture (Section)	1×10^{-10} / hr
Pipes<3"	Rupture	1×10^{-9} / hr
Pumps	Failure to Start	1×10^{-3} /D
	Failure to Run (Normal)	3×10^{-5} / hr
	Failure to Run (Extreme ENV)	1×10^{-3} / hr
RELAYS	Failure to Energize	1×10^{-4} /D
	Failure HO Contact to Close	3×10^{-7} / hr
	Short Across HO/NC Contact	1×10^{-8} / hr
	Open NC Contact	1×10^{-7} / hr
SOLID STATE DEVICES — Hi PWH Application	Fails to Function	3×10^{-6} / hr
	Shorts	1×10^{-6} / hr
SOLID STATE DEVICES — Low PWH Application	Fails to Function	1×10^{-6} / hr
	Shorts	1×10^{-7} / hr
Switches	Limit: Failure to Operate	3×10^{-4}/D
	Torque: Failure to Operate	1×10^{-4}/D
	Pressure: Failure to Operate	1×10^{-4}/D
	Manual: Faiure to Transfer	1×10^{-5}/D
	Contacts Short	1×10^{-8}/hr

FAILURE MODE		MEDIAN FAILURE RATE
TRANSFORMERS	Open CXT	1×10^{-6} / hr
	Short	1×10^{-6} / hr
Valves (HOV)	Failure to Operate	1×10^{-3} /D
	(Plug) Failure to Remain Open	1×10^{-4} / D
	External Leak or Rupture	1×10^{-8} / hr
Valves (SOV)	Failure to Operate	1×10^{-3} / D
Valves (AOV)	Failure to Operate	3×10^{-4} / D
	(Plug) Failure to Remain Open	1×10^{-4} / D
	External Leak or Rupture	1×10^{-8} / hr
Valves (Check)	Failure to Open	1×10^{-4} / D
	Reverse Leak	3×10^{-7} / hr
	External Leak or Rupture	1×10^{-8} / hr
Valves (Vacuum)	Failure to Operate	3×10^{-5} / D
	Rupture	1×10^{-8} / hr
Valves, Orifices, Flow Meters (Test)	Rupture	1×10^{-8} / hr
Valves (Manual)	Failure to Remain Open (Plug)	1×10^{-4} / D
Valves (Relief)	Failure to Open/D	1×10^{-5} / D
	Premature Open/hr	1×10^{-5} / hr
Welds	Leak	3×10^{-8} / hr
Wires	Open	3×10^{-5}/hr
	Short to GND	3×10^{-7}/hr
	Short to PWR	1×10^{-8}/hr

TABLE IV
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, this high error rate would not apply.
10^{-1}	Personnel on different work shifts 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 inspections, assuming no checklist 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 V

Human Error Rate as a Function of Response Time

Response Time(s)

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 x 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.

The value of F_i is the probability that a person will die if the ith event occurs. This value depends on the oxygen concentration, the duration of exposure and the difficulty of escape. For convenience of calculation, a relationship between the value of F_i and the lowest attainable oxygen concentration is defined (Figure 1). The lowest concentration is used rather than an average since the minimum value is conservative and not enough is understood to allow the definition of an averaging period. 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 0 to be 10^{-7} per hour if the expected rate of occurrence of the event were one per hour. At decreasing concentrations the value of F_i should increase until, at some point, the probability of dying becomes unity. That point was selected to be 8.8% oxygen, the concentration at which one minute of consciousness is expected.

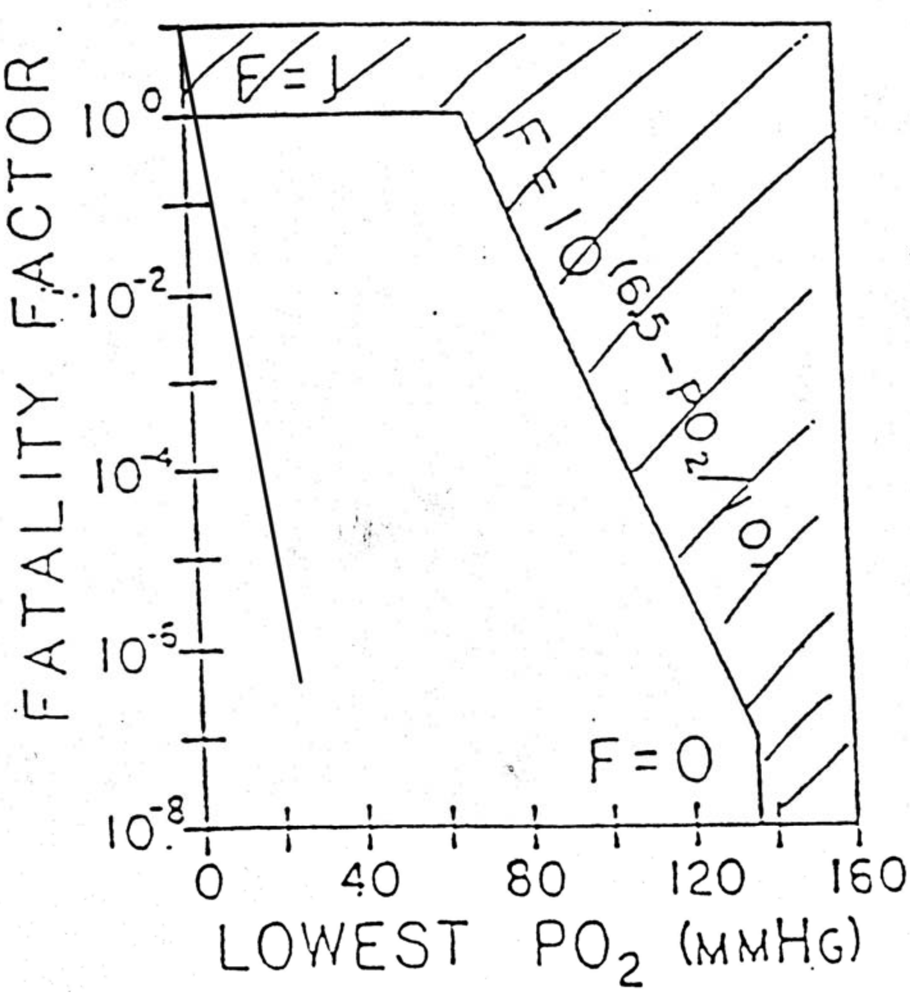


Fig. 1. Graph of the logarithm of the fatality factor (F_i) versus the lowest attainable oxygen concentration which can result from a given event. This relationship should be used when no better estimate of the probability of fatality from a given event is available.

The oxygen concentration is a confined volume during and after a release of inert gas may be approximated from the following differential equation

$$V\frac{dC}{dt} = 0.21Q - (R + Q)C \qquad (2)$$

where

V = the confined volume (ft^3 or m^3)
C = the concentration of oxygen
R = the spill rate into the confined volume (cfm or m^3/s)
Q = the rate of ventilation through the confined volume (cfm or m^3/s).

In order to solve this differential, the following assumptions are made:

- Complete, instantaneous mixing takes place in the confined volume
- V, R, Q, and the total pressure remain constant
- The initial oxygen concentration is 21%.

Therefore, the oxygen concentration during the release is

$$C_R(t) = \left(\frac{21\%}{Q+R}\right)\left[Q + R\exp\left[\frac{(Q+R)}{-V}t\right]\right], \qquad (3)$$

where t is the time from the start of the release. After the release has ended, the oxygen concentration is

$$C_E(t) = 21\%\left[1 - \exp\frac{(Qt)}{-V}\right] + C_R(t_e)\exp\frac{(Qt)}{-V} \qquad (4)$$

where t is the time after the end of the release (when R becomes zero) and te is the duration of the release.

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

TABLE VI

Oxygen Deficiency Hazard Class

ODH Class	ϕ (hr-1)
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	$\geq 10^{-1}$

ODH controls

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. The following logic tree describes suggested minimum control measures to allow an individual to participate in a given ODH Class 1 or greater operations.

TABLE VII

ODH Control Measures

	ODH Hazard Class			
Environmental Controls	1	2	3	4
1. Warning Signs	X	X	X	X
2. Installed Oxygen Monitor	X	X	X	X
3. Ventilation	X	X	X	
ODH Qualified Personnel Controls				
4. Medical Approval as ODH Qualified		X	X	X
5. ODH Training	X	X	X	X
6. Personal Oxygen Monitor		X	X	
7. Self-Rescue Supplied Atmosphere Respirator		X	X	
8. Multiple Personnel in Communication	X	X	X	X
9. Unexposed Observer			X	
10. Self-contained Breathing Aparatus				X
ODH Restricted Personnel Controls				
11. Must not be ODH Excluded		X	X	N/A
12. ODH Briefing	X	X	X	N/A
13. Self-Rescue Supplied Atmosphere Respirator		X	X	N/A
14. One-to-One Escort by ODH Qualified Personnel		X	X	N/A

X = Required
N/A = Not applicable, ODH restricted personnel shall not be exposed to ODH Class 4 operations

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

1. Significant potential 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 conclusion.

6. Special requirements
   a. Area oxygen monitors
   b. Self-rescue supplied atmosphere respirators
   c. Unusual procedures

Example: Oxygen-Deficiency Hazard Analysis in BGO Area

by L. M. Bollinger

The hazard of interest is the liquid nitrogen in a standard 160-ℓ dewar. This dewar is located in a partially enclosed space 12 ft. high, 34 ft. long, and ~14 ft. wide, with a 3.5-ft. wide opening at each end. The opening extends from floor to ceiling, and at the top of each opening a fan with a capacity of ~1200 CFM blowing out of the room, thus forcing air to circulate into the room at floor level through each opening. See layout of area in attached sketch.

From the above data one calculates that the volume of the room is ~160 m^3 and the forced ventilation capacity if ~1.1 m^3/sec. In addition, because both spacings are from floor to ceiling, the inherent ventilation caused by convection and diffusion is good.

Analysis – use Fermilab approach in Document #5064

Scenario #1

The most probable accident is that the LN_2 line between the dewar and the distribution manifold breaks. Janssens estimates that the breakage probability is ~10^{-1} yr^{-1}. Even if the LN_2 line is severed at the output from the dewar, the LN_2 emission rate is only ~0.3 ℓ/sec, as measured on 3/1/91 at a dewar pressure of 23 psi. At this pressure, after vaporizing and warming to room temperature, the expansion ratio for LN_2 is $[(1.3054\}1.134 \times 10^{-3}]^{-1} = 675$. Thus the N_2 gas emission rate is 0.20 m^3/sec.

Assuming complete mixing for the N_2 and air (a reasonable assumption for such good ventilation and low N2 emission) the minimum concentration of O_2 in room is

$$C\frac{min}{O_2} = \frac{0.21}{1+Q/R}\left\{\frac{Q}{R} + \exp\left[-\left(\frac{Q}{R}+1\right)V/V_o\right]\right\}$$

where $Q \equiv$ exhaust rate = 1.1 m^3/sec

$R \equiv$ emission rate = 0.2 m^3/sec

$V \equiv$ volume of N_2 = 0.160 (675) = 108 m^3

$V_o \equiv$ volume of room = 160 m^3.

Thus,

$$C_{O_2}^{min} = \frac{0.21}{1+5.5}\left\{5.5+\exp\left[-(5.5+1)\frac{108}{160}\right]\right\}$$

$= 0.178$

The partial pressure corresponding to this is

$$P_{O_2} = 0.178\,(740) = 131.7\ \text{Torr.}$$

According to the Fermilab safety document 5064, the probability of fatality F is

$$F = 10^{(6.5-0.1P_{O_2})}$$

∴

$$F = 10^{6.5-13.2} = 10^{-6.7} = 2 \times 10^{-7}$$

Thus, the fatality rate for scenario #1 is

$$\phi = 10^{-1}\,(2 \times 10^{-7}) = 2 \times 10^{-8}\ \text{yr-1},$$

which is small enough to be ignored.

Scenario #2

The worst credible incident for the LN_2 dewar is one in which the main LN_2 tube at the top of the dewar is accidentally severed. This would require a massive blow since the tube is solid SS. This scenario is similar to scenario #1 except that there the line is restricted to a 3/8" orifice by the output fitting whereas here the 5/8" dewar line is 5/8" dia. Since the line itself plays a significant role in limiting the flow of LN_2 in both cases and since one is dealing with 2-phase flow in both cases, it is estimated that the flow rate of scenario #2 relative to scenario #1 cannot be increased more than the ratio of output-aperture areas. That is, the flow rate is $<0.3\ (5/3)^2 =$ 0.83 ℓ/sec. At this flow rate,

$$C\frac{\min}{O_2} \leq \frac{0.21}{1+1.3}\left\{1.3+\exp\left[-(1.3+1)\frac{108}{160}\right]\right\}$$

$$= \qquad 0.139$$

and

$$P_{O_2} = 103\ \text{Torr}$$

$\therefore$

$$F = 10^{-3.8} = 1.6 \times 10^{-4}.$$

The probability of such an accident can be estimated from experience in the Physics Division, where no such accident has ever occurred in about 40 years of experience. At least 10 dewars are present in the building on an average. Thus, the accident rate P is

$$P \leq (400\ \text{yr})^{-1} = 2.5 \times 10^{-3}\ \text{yr-1}$$

The facility rate for this scenario is

$$\phi < (2.5 \times 10^{-3})\ (1.6 \times 10^{-4}) = 4 \times 10^{-7}\ \text{yr}^{-1}$$

Again, this risk is small enough to be ignored.

Scenario #3

Consider the consequences if all of the LN_2 content of the dewar were released very rapidly. This scenario is not credible since no large source of energy is present in the area.

To be specific, let the LN_2 be emitted and be vaporized at a rate of 5 ℓ/sec. This gives 3.25 m3 of gas per sec. In this case,

$$C_{O_2}^{min} \leq \frac{0.21}{1+0.34}\left\{0.34+\exp\left[-(0.34+1)\frac{108}{160}\right]\right\}$$

$$C_{O_2}^{min} + 0.117, \quad P_{O_2} = 88.0 \text{ Torr}$$

For this value,

$$F = 10^{(6.5-8.8)} = 5 \times 10^{-3}.$$

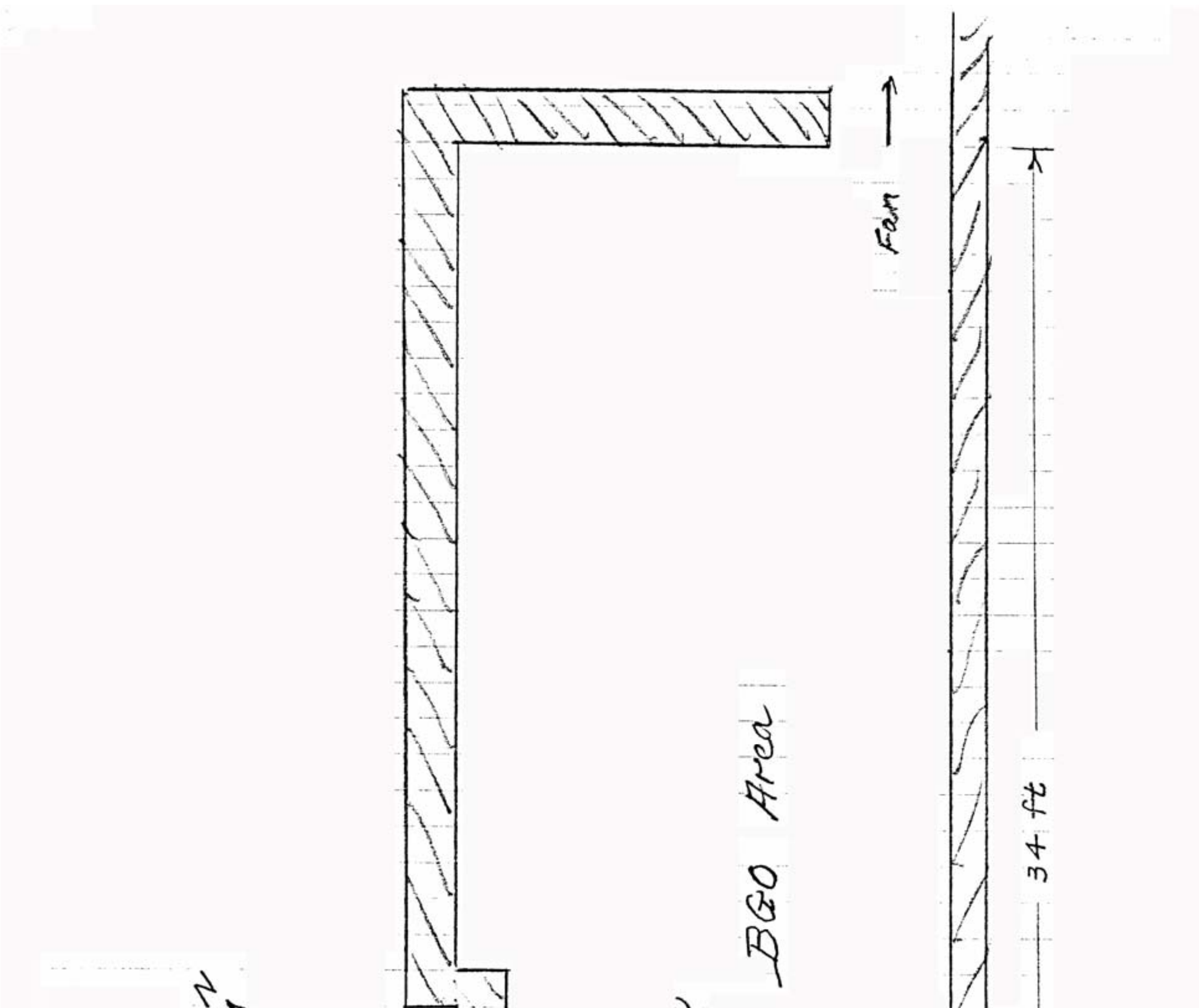
Thus, using same P as in scenario #2

$$\phi \leq (2.5 \times 10^{-3})\,(5 \times 10^{-3}) = 1.25 \times 10^{-5}\ y^{-1} = 1.4 \times 10^{-9}\ hr^{-1}$$

This value is small enough that no special precautions are needed. Moreover, the actual fatality rate is much smaller than ϕ because the occupancy rate of the area is very small (~0.02) averaged over a year.

Conclusion

The LN_2 dewar in the BGO area is not a significant ODH hazard.



Fan
BGO Area
34 ft
N
LN_2 Dewar
Fan