ARGONNE NATIONAL LABORATORY

HIGH ENERGY PHYSICS DIVISION

AWA

ARGONNE WAKEFIELD ACCELERATOR

OXYGEN-DEFICIENCY ANALYSIS IN THE AWA BUNKER (REVISED IN MAY 2002)

Prepared by: Manoel Conde

Approved:

HEP-AWA Group Rep: _____ **Date:** 3/19/07
Wei Gai

HEP-ESH Administrator: _____ **Date:** 3/19/07
Leon T. Reed

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9700 South Cass Avenue, Argonne, Illinois 60439

FAX: (630) 252-5076

conde@anl.gov
(630) 252-6099

January 23, 2002

To: D. Jankowski HEP safety coordinator

From: M. Conde MEC HEP (AWA)

Subject: **Review Usage of Liquid Nitrogen in Argonne Wakefield Accelerator Bunker**

On April 26, 2001, a safety review committee was convened to address potential safety issues evolving from the use of liquid nitrogen in the AWA bunker. As a result of that review, it was agreed that the AWA group would provide an analysis of the risks associated with the presence of a dewar with liquid nitrogen in the AWA bunker.

This analysis is shown in the attached document "Oxygen-Deficiency Analysis in the AWA Bunker". The analysis reaches the conclusion that the hazard associated with the intended use of the dewar in the AWA bunker is classified as an Oxygen Deficiency Hazard Class 0, which requires no protective measures to further reduce the risk of fatality.

Oxygen-Deficiency Analysis in the AWA Bunker

Manoel Conde

January 2002

The hazard of interest is the liquid nitrogen in a standard 80-liter dewar. This dewar will be brought into the AWA bunker only when it is necessary to vent the AWA vacuum system. It is estimated that this will happen, in average, once every two months. On these occasions the dewar will remain in the AWA bunker for a period of approximately two to six hours.

The AWA bunker is housed in Building 366 and built by large concrete blocks. It is about 75 ft long, 10 ft wide, and 7.5 ft high, with a total internal volume of 5722 ft^3 (162 m^3). Figure 1 shows the layout of the bunker and the location of its two doors, each one being 7 ft high and 33 inches wide. Three floor fans are normally situated on the positions marked in Figure 1, and provide air circulation when the machine is not in operation. These fans should be set to "high" when the liquid nitrogen dewar is brought into the bunker, in order to guarantee a high air exchange between the bunker and the rest of the building. Under these conditions the air flow through the doors was measured (Fig. 2), yielding a total exhaust rate of 1500 CFM (0.71 m^3/s).

The analysis in this document is based on a similar analysis shown in the Physics Division Cryogenic Safety Manual. The goal of the Oxygen Deficiency Hazard (ODH) risk assessment is to estimate the rate at which fatalities will occur as a result of exposure to reduced-oxygen atmospheres. The oxygen deficiency hazard fatality rate (D) for a given event is defined as the product of the expected rate of that event (P) by the fatality factor for the event (F):

$$D = P\,F$$

Since there will be no liquid nitrogen transfer in the bunker, the worst credible accident is one in which the main liquid nitrogen tube at the top of the dewar is accidentally severed. This would require a massive blow, since the tube is solid stainless steel and is well protected by the structure of the dewar. According to the Physics Division Cryogenic Safety Manual, the probability of such an accident can be estimated from the experience in the Physics Division, where no such accident has ever occurred in over 40 years of experience. At least 10 dewars are present in the building on an average. Thus, the accident rate P is

$$P \le (400\ yr)^{-1} = 2.5\times10^{-3}\ yr^{-1}$$

The value of the fatality factor (F) depends on the oxygen concentration, the duration of exposure and the difficulty of escape. For convenience of calculation we will use the same relationship that was used in the Physics Division Cryogenic Safety Manual, relating F to the lowest attainable oxygen concentration (C_{oxy}):

$$D = P\,F = 2.5\times10^{-3}\,yr^{-1}\times2.0\times10^{-5} = 5.0\times10^{-8}\,yr^{-1}$$

This very low number puts the analyzed hazard as an Oxygen Deficiency Hazard Class 0, which requires no protective measures to further reduce the risk of fatality. This would be the case even if the dewar were kept in the bunker all the time.

Even if worse scenarios are considered — for example a reduction of the exhaust rate by a factor two, as shown in Fig. 3(b), or a catastrophic explosion of the dewar, releasing all the liquid nitrogen in a fraction of a second — the lowest attainable oxygen concentration would have approximately the same value we just calculated. Thus, the hazard would still be classified as an Oxygen Deficiency Hazard Class 0.

40	90	85
60	70	85
70	70	85
70	80	100
80	90	90
70	90	80
85	85	70

Figure 2: Measured air flow through Door #2 of AWA Bunker. Each rectangle is 11 inches wide and 12 inches high. The numbers correspond to the air flow in ft/min measured by an Alnor air flow gauge model #9870.

Argonne National Laboratory

Argonne, Illinois 60439

PHYSICS DIVISION

CRYOGENIC SAFETY MANUAL

Prepared by: J. R. Delayen
R. A. Schlenker
K. W. Shepard
J. R. Specht
L. Young

October 1991

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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

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 liquid helium and nitrogen 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 liquid helium and nitrogen 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.

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 use of liquid nitrogen in the Physics Division.

6. 29 CFR 1910.103(c) - *Liquified 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.

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.

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. 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.

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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

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 chain 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].

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

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

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

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

The actual heat flow Q is given by:

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

IV. Helium from 15 K to 77 K (T_f = 46 K, ΔT = 26 K) $k_f = 4.52\times10^{-4}$ W/cm K, $\rho_f = 1.06\times10^{-3}$, $\mu_f = 60\times10^{-6}$ poise, thus

$$h_c = \frac{1}{2}\left[\frac{(4.52\cdot10^{-4})^3(1.06\cdot10^{-3})^2 980 \times 5.5}{60\cdot10^{-6}\cdot 46}\right]^{1/4}\left(\frac{\Delta T}{L}\right)^{1/4}$$

$$= 1.89\times10^{-3}\left(\frac{\Delta T}{L}\right)^{1/4} \text{Watt/cm}^2\ \text{K}$$

V. Helium from 77 K to 293 K (T_f = 185, ΔT = 216) $k_f = 1.11\times10^{-3}$ W/cm K, $\rho_f = 2.64\times10^{-4}$, C_p = 5.5 J/gm K, $\mu_f = 148\times10^{-6}$ poise

$$h_c = \frac{1}{2}\left[\frac{(1.11\times10^{-3})^3(2.64\times10^{-4})^2 \times 980 \times 5.5}{148\times10^{-6} \times 185}\right]^{1/4}\left(\frac{\Delta T}{L}\right)^{1/4}$$

$$= 1.04\times10^{-3}\left(\frac{\Delta T}{L}\right) \text{Watt/cm}^2\ \text{K}$$