Lecture 16
Safety in Cryogenic Systems

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Goals

- Provide an overview of safety issues in cryogenics
- Describe the hazards and mitigations associated with the excess pressure in cryogenic systems
- Describe Oxygen Deficiency Hazards and their mitigations
- **Warning: This is NOT a complete safety class**
- **Additional information may be found in monographs, bulletins of the Compressed Gas Association and in the ES&H manuals of the various national labs (Fermilab, JLAB, SLAC etc)**

Some Basic Safety Issues

- Cryogenic fluids and their boil off gases are extremely cold and can cause burns (frost bite) and damage to eyes
  - Always wear safety glasses and protective gloves when handling cryogenic fluids or when touching things that may have contacted cryogenic fluids
- Be aware that if cryogenic fluids come in contact with materials that are aren’t designed for that temperature it can lead to sudden failure of the material
- If surfaces cooled to cryogenic temperatures are exposed to room air the air will condense on the surface and due to its higher boiling point the condensate will be oxygen rich. – this can result in a significant fire hazard
  - Always insulate surfaces to keep them above cryogenic temperatures
- <u>Never</u> inhale Helium from balloons etc
- Safety considerations should be designed in from the beginning. Retrofits are time consuming & expensive

Some Special Cases

- Hydrogen – extremely flammable
- Oxygen (LOX) can cause almost anything to burn
- LNG – extremely flammable
- We will spend the rest of our time on two specific safety issues associated with cryogenics
  - Over Pressurization
  - Oxygen Deficiency Hazards

Over Pressurization

- A hazard results from the large volume expansion that occurs when a cryogenic liquid is converted to 300 K gas
- As a result large pressure rises are possible
- This could easily result in material failures, and explosive bursting

Volume Changes for Cryogenic Fluids from normal boiling point to 300 K & 1 atm

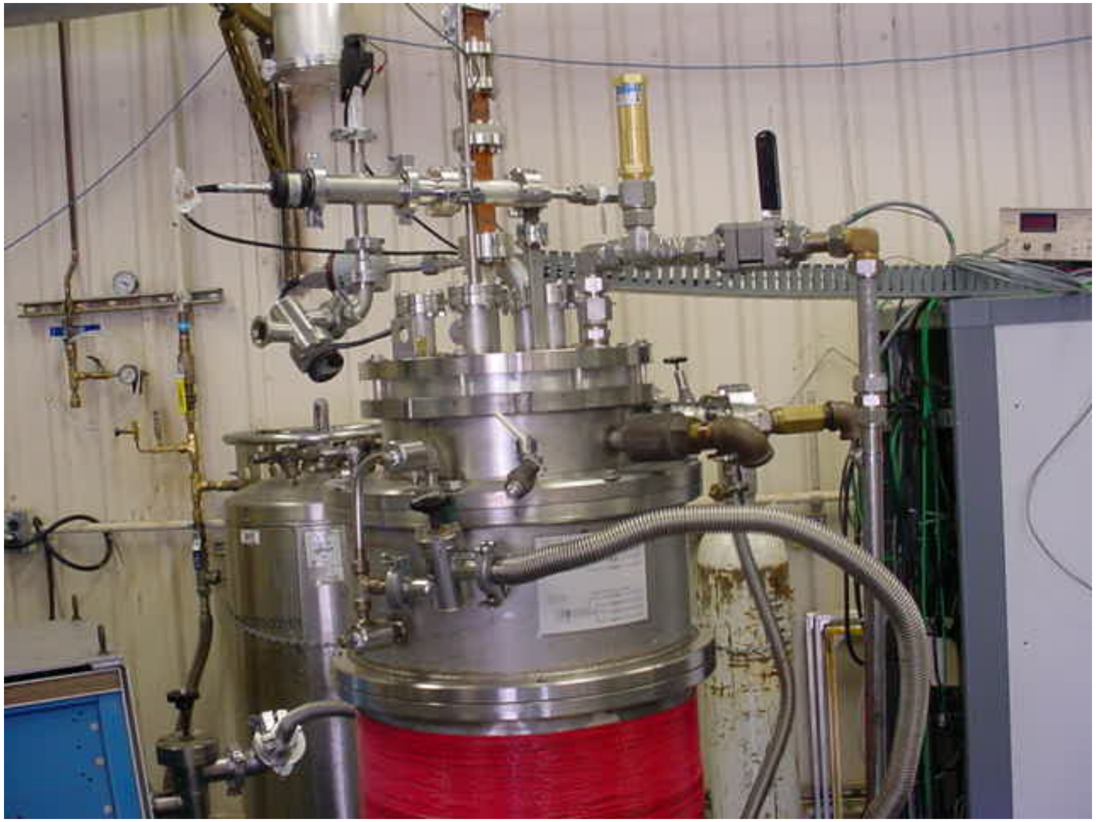
Substance	V_{gas}/V_{liquid}
Helium	701
Parahydrogen	788
Neon	1341
Nitrogen	646
Argon	779
CO_2	762
Oxygen	797

The solution is to always install pressure relief devices

- Redundant devices should be used. Typically relief valve + burst disc
- The device should be set to open at or below the MAWP of the vessel
- Valves should be sized for worst case scenarios
- Valves should be tested & certified before installation
- Ensure that there are no trapped volumes. Remember – valves may leak or be operated incorrectly and cryogenic systems may warm up unexpectedly (vacuum spaces need relief valves as well)
- Never store cryogenic liquids in a container without a relief system

Relief Devices Continued

- Do not put shut off valves between system and relief valves
- Ask What If ? questions



Comments on Relief Calculations

- What is the worst case?
  - Typically this is taken as a catastrophic failure of the vacuum space – thus admitting air into the cryostat.
  - The air condenses onto the cold surface and in doing so deposits heat into the liquid cryogen causing rapid boiling and expansion
  - This effect (~ 0.6 - 4 W/cm^2) is far more significant than the increased heat leak from 300 K due to the spoiling of the vacuum
    - » Note that 0.6 W/cm^2 assumes the presence of MLI on cold surfaces

Oxygen Deficiency Hazards

- Gases used in cryogenic systems such as He, N_2, Ar, H_2 can displace oxygen in an area causing the area to be unsafe for human life
  - Any oxygen concentration less that 19.5 % is considered oxygen deficient (OSHA)
- There are several aspects to this problem
  - Large volume changes from cryogenic liquids to room temperatures gases
  - Little or no warning of the hazard at sufficiently low O_2 concentrations
  - Consequences can easily be fatal
- <u>This is not just a problem in large cryogenic installations</u>
  - It can easily be a problem in small labs and university settings – in fact, complacency in smaller settings may be an added risk factor

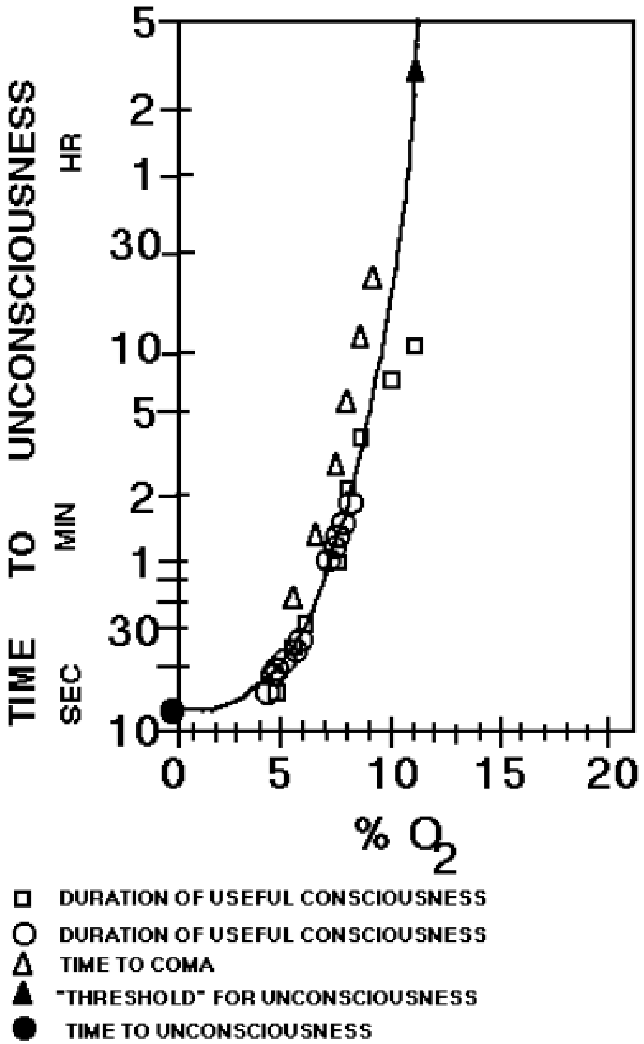
Oxygen Deficiency Hazards

- Recall the large volume increase between a cryogenic liquid and its gas at 300 K and 1 atmosphere
- Even small amounts of liquid can be a hazard is the if released into a small enough volume e.g. small rooms, elevators or cars

Consequences of Oxygen Deficiency

Volume % Oxygen (at sea level)	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	Spasmodic breathing Convulsive movements Death in 5-8 minutes

Approximate time of useful consciousness for a seated subject at sea level vs % O_2



At low enough concentrations you can be unconscious in less that a minute with NO warning

This is one of the things that makes ODH so dangerous & frequently results in multiple fatalities

Its also why inhaling He from balloons is dangerous

ODH Safety Basics

- Understand the problem: This lecture
- Determine level of risk
- Apply mitigations to reduce the risk
- Have a plan to respond to emergencies
- ALL users of cryogenic fluids no matter how small should analyze their risk and consider mitigations
  - At a minimum, everyone should be trained to understand the hazard

Determining ODH Risk

- For each use of cryogenic liquids or inert gases a formal written analysis of the risk ODH posed should be done. The details of this may vary from institution to institution and may be driven by regulatory requirements.
- One technique used by many US laboratories (Fermilab, Jlab, SLAC, BNL) is the calculation of a ODH Fatality Rate. The size of this rate is then tied to a ODH class and each class is linked to specific required mitigations

ODH Fatality Rates

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

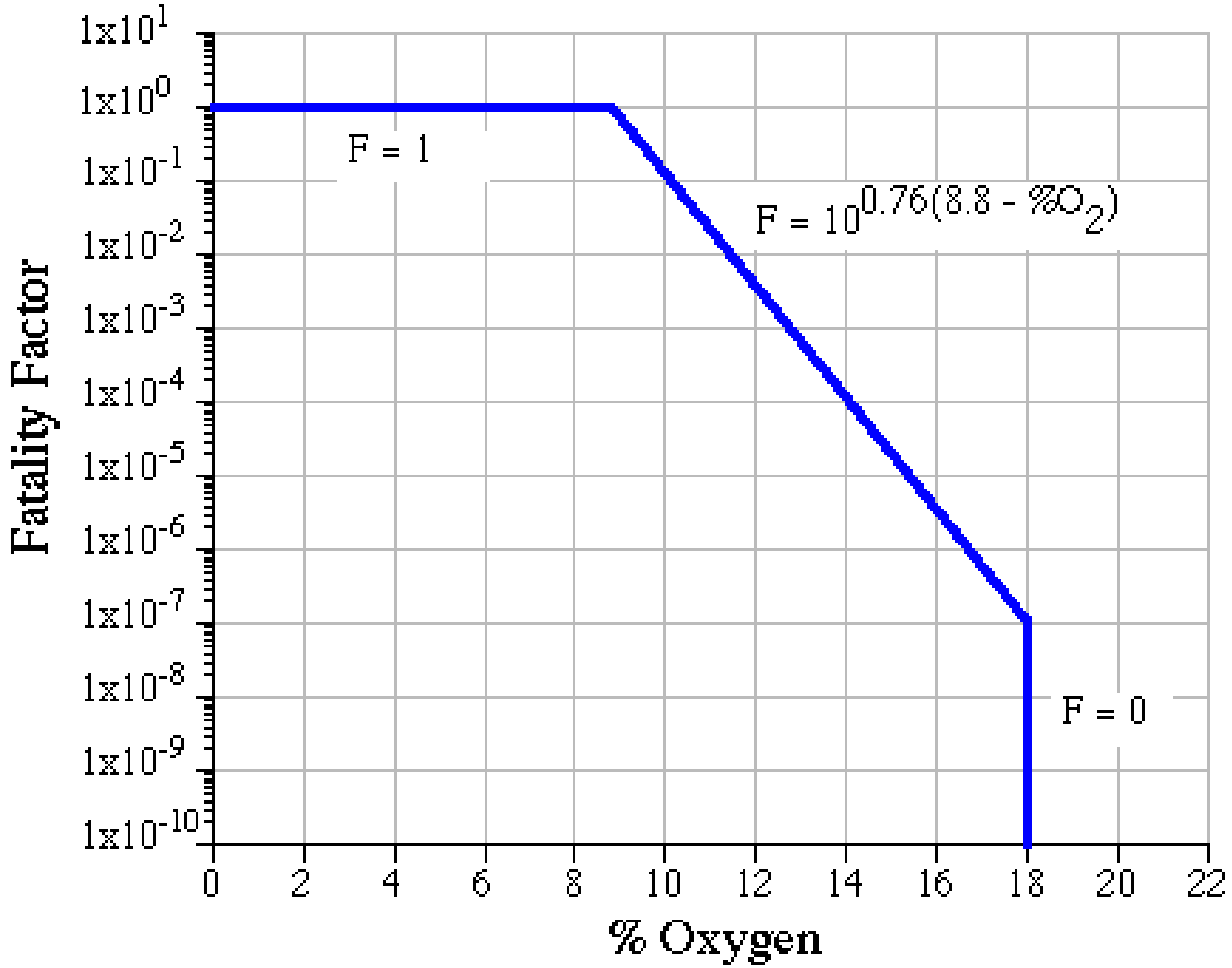
where: Φ = the ODH fatality rate (per hour)
P_i = the expected rate of the ith event (per hour), and
F_i = the probability of a fatality due to event i.

Sum up for all n possible events

ODH Fatality Rates

- Probability of an event (P_i) may be based on institutional experience or on more general data (see handouts)
- Probability of a given event causing a fatality (F_i) is related to the lowest possible oxygen concentration that might result from the event

F_i vs. Oxygen Concentration (note limits) from "Cryogenic and Oxygen Deficiency Hazard Safety: ODH Risk Assessment Procedures" SLAC ES&H Manual



Example ODH classes at SLAC

- Example ODH classes at SLAC
  Class 0 means no hazard
  Class 4 is not allowed
  Class 1 – 3 require mitigations to reduce risk

ODH Class	Φ (hr^{-1})
0	$< 10^{-7}$
1	$> 10^{-7}$ but $< 10^{-5}$
2	$> 10^{-5}$ but $< 10^{-3}$
3	$> 10^{-3}$ but $< 10^{-1}$
4	$> 10^{-1}$

ODH Mitigations

- Best solution: Eliminate the hazard by design choices
  - Reduce inventory of cryogenic fluids & compressed gases
  - Don't conduct cryogenic activities in small spaces
  - Don't use LN2 underground
- Training
  - Everyone working in a possible ODH area should be made aware of the hazard and know what to do in the event of an incident or alarm
    - This includes periodic workers such as security staff, custodial staff and contractors
    - Visitors should be escorted
- Signs
  - Notify people of the hazard and proper response
  - Indicate that only trained people are authorized to be there

ODH Mitigations

- Ventilation systems to increase air exchange and reduce the possibility of an oxygen deficient atmosphere forming
  - **Warning** If this approach is taken, the ventilation system must now be treated as a safety system with appropriate controls and redundancies
    - » What happens during maintenance or equipment failure?
    - » How do you know ventilation system is working?
- ODH Monitors and Alarms
  - A very common and effective mitigation. Commercial devices exist.
  - Indicates when a hazard exists
  - Very valuable in showing if a area has become dangerous during off hours
  - Alarms generally set to trip at 19.5% Oxygen
  - Alarms should include lights & horn as well as an indicator at entrance to area
  - Alarms should register in a remote center (control room or fire dept) as well
  - As a safety system it requires appropriate controls & backups (UPS, redundancy etc)
  - In some cases personal monitors will add additional safety

Response to Alarms & Emergencies

- In the event of an alarm or other indication of a hazard immediately leave the area
- Do not reenter the area unless properly trained and equipped (e.g. supplementary air tanks)
  - Don't just run in to see what the problem is
- Only properly trained and equipped professionals should attempt a rescue in an ODH situation
- Response to alarms should be agreed upon in advance, documented and be part of training

ODH Summary

- Oxygen Deficiency is a significant hazard in cryogenic installations both large and small. It must be taken seriously
- Lethal conditions can exist without prior warning or symptoms
- ODH can managed by awareness, analysis of risk and appropriate mitigations
- Everyone working in a cryogenic facility should be aware of the risk and know what to do in the event of a problem
- There is a significant amount of experience & help available from laboratories and industry to reduce the ODH risk

General Cryogenic Safety Guidelines

EUROPEAN SPALLATION SOURCE

- Perform a formal hazard analysis on any cryogenic system or process prior to the start of work and design. Identify the hazards and how you will mitigate them. Ask "What If" questions. Keep in mind that equipment breaks, cryogenic fluids can turn rapidly into gas, valves leak or are improperly operated and vacuums can fail. This analysis should be done regardless of the size or complexity of the cryogenic system.
- Design safety into equipment and processes from the beginning. Adding safety features at the end of the design process can be expensive, time consuming and may result in hazards being missed. Note that it is always better to remove a hazard via engineering design than to try to mitigate the hazard.
- Review, Review, Review. Everyone, even experts, miss things or make mistakes. Having the safety of your cryogenic system reviewed by other people, be they other members of your team, external consultants or formal review committees is key to improving the likelihood of a safe system.
- Whenever working with cryogenic liquids or inert gases, no matter how small the amount, always consider the possibility that an Oxygen Deficiency Hazard (ODH) may exist. Either prove by analysis that such a hazard doesn't exist or apply appropriate design changes or mitigations to eliminate or reduce the hazard. ODH issues are particularly dangerous due to the large volume of gas evolved by even small amounts of cryogenic liquid and by the fact that in low enough oxygen concentrations, the first physiological symptom can be sudden unconsciousness, followed rapidly by coma and death.
- Take advantage of existing regulations and industry codes and standards to develop a safe cryogenic system.
- Never disable or remove safety devices, relief valves or operate systems outside their operating parameters.
- Only use materials at cryogenic temperatures that have been proven to work at those temperatures. Keep in mind during the hazard analysis that materials that nominally operate at room temperature (such as the outer walls of vacuum vessels) could reach cryogenic temperatures in certain failure modes.
- Ensure that everyone working with or around cryogenic systems, even casual or periodic users, have the appropriate level of training in cryogenic and ODH safety.
- Always use required Personal Protective Equipment and follow required operating procedures. Taking shortcuts frequently leads to accidents.
- Be aware that surfaces exposed to air and colder than 77 K will start to condense the air and that the condensate will be oxygen rich (due to the higher boiling point of oxygen). This can lead to an enhanced flammability hazard. Insulate surfaces to prevent air condensation.
- Working with hydrogen, oxygen and LNG presents additional flammability hazards not present with inert cryogenic fluids and thus requires additional specialized knowledge. Make sure that such expertise is present in the designing, reviewing and operating of these systems.
- Take advantage of existing information & expertise. There are significant resources available on cryogenic safety. These include books, pamphlets, research papers, codes & standards, websites and conferences. Cryogenic safety standards from other institutions such as Fermilab may also provide valuable information. The use of experts from other institutions as external reviewers or consultants may be beneficial.