Lecture 16
Cryogenic Safety

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Cryogenics Presents
Unique Safety Hazards

- Behavior of materials at cryogenic temperatures
- Impact of cryogens on people
- Over pressurization and bursting hazards due to large volume changes between liquid and vapor
- Oxygen deficiency hazards
- Flammability of hydrogen or LNG
- Impact of LOX on combustibility of materials
- Large amounts of stored energy in superconducting magnet systems
- **Hazards (sometimes lethal) exist in all sizes of cryogenic installations from the largest industrial site to the smallest university lab**

Cryogenic Hazards are Manageable

- Always conduct a safety analysis of a cryogenic system - no matter how small the system
- Consider safety from the beginning of the design
  - Retrofitting can be very expensive
  - Consider both normal and all possible abnormal operating conditions
  - Ask “what if “ questions
- Have safety calculations and designs reviewed either internally or externally
- Build redundancy into safety systems – no single point failure should cause a hazard
- Ensure personnel are aware of hazards and properly trained
- Take advantage of previous work and outside resources - Codes, Regulations, National Labs, CGA

Class Content

- During this lecture, I will cover some, but not all, cryogenic safety issues
  - Impact of Material Choices & General Cryogenic Safety
  - Oxygen Deficiency Hazards
  - Pressure Safety in Cryogenics
- I will illustrate with example accidents to show what can go wrong
- I will list best practices for each topic covered
- I will provide lists of resources for additional learning
- Please ask questions

Impact of Material Choices & General Cryogenic Safety

Example Accident

- October 20, 1944, Cleveland, Ohio
  - Sudden failure of an LNG tank at the East Ohio Gas company releases 1.1.million gallons of LNG which quickly ignites causing fires and explosions
  - LNG and very cold gas vapor flows into sewar system spreading the fire
  - A second LNG tank fails due to the fire releasing an additional 500,00 gallons of LNG that also ignites
  - LNG plant is located in a mixed residential and industrial neighborhood
  - 128 deaths, damage to more than 200 buildings (80 of which completely destroyed) Roughly 3600 people made homeless

Resulting damage from the 1944 Cleveland LNG Fire and explosion. Gas plant located in the upper half of the picture; note destroyed homes, factories and other buildings in the lower half

What Happened ?

- The Impact of the Cleveland fire greatly delayed the use of LNG storage in the USA
- Its important to point out that today's LNG systems are <u>much safer</u> – for starters we put storage facilities in remote locations.
- No official, single cause of the event was determined. However, suspicion did fall on the material of the LNG tank (3.5% nickel low carbon steel) This material was known to be brittle at these temperatures but was judged suitable for use and had been used successfully on other LNG tanks. One of the recommendations of the resulting Bureau of Mines investigation was that such material should not be used in the particular cylindrical tank design employed in Cleveland unless it could be established conclusively that the material choice was not a cause of the accident. This material is not used today for LNG systems
- An additional contributing factor was the higher density of the cold gas allowing it to seep into sewars etc. This was an unanticipated effect. Minimal containment dikes surrounded the tanks (this is also different today)

Material Choices & Safety

- Properties of both cryogenic fluids and solid materials can affect safety
  - Some materials inappropriate for cryogenic use
  - Material properties change greatly with temperature and these changes may cause safety issues
- Many failures of cryogenic systems can be traced to either using the wrong material or not taking into account the property changes.

Some Appropriate Materials for use in Cryogenics

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Austenitic stainless steels e.g. 304, 304L, 316, 321
Aluminum alloys e.g. 6061, 6063, 1100
Copper e.g. OFHC, ETP and phosphorous deoxidized
Brass
Fiber reinforced plastics such as G –10 and G –11
Teflon (depending on the application)
Niobium & Titanium (frequently used in superconducting RF systems)
Invar (Ni /Fe alloy)
Indium (used as an O ring material)
Kapton and Mylar (used in Multilayer Insulation and as electrical insulation
Quartz (used in windows)

Some Unsuitable Materials for Use in Cryogenics

Martensitic stainless steels - undergoes ductile to brittle transition when cooled down.
Cast Iron – becomes brittle
Carbon steels – becomes brittle.
Rubber and most plastics (important exceptions are Kel-F and UHMW used as seats in cryogenic valves)

- Notes:
  - Carbon steels are sometimes used for room temperature vacuum vessels surrounding cryogenic systems – Care must be taken to ensure that any possible leaks will not result in cooling the outer vessel material below its ductile to brittle transition temperature
  - Always check that flows from relief valves etc. do not cool down a nearby material that is not appropriate fro cryogenic use.

Other Issues with Cryogenic Properties of Materials

- Even those materials that are appropriate for use in cryogenics have properties that change significantly as a function of temperature. These changes have to be allowed for in the design and may have safety implications. Two examples of this are Thermal Contraction and Material Strength.

- Thermal Contraction – most (though not all) materials used in cryogenics contract upon cooling from room temperature to cryogenic temperatures. This contraction can lead to:
  - Unplanned contacts or gaps between adjacent components. This may lead to a material not suitable for cryogenic being cooled down to cryogenic temperatures
  - High stress and possible failure in components that are over constrained and don't allow for this contraction. This is commonly seen in wiring systems that aren't designed for the contraction.
  - Unexpected changes in alignment
- Always allow for thermal contraction in system designs

Thermal Contraction Can Be Quite Significant

Material	ΔL / L (300 K – 100 K)	ΔL / L (100 K – 4 K)
Stainless Steel	296 x 10^{-5}	35 x 10^{-5}
Copper	326 x 10^{-5}	44 x 10^{-5}
Aluminum	415 x 10^{-5}	47 x 10^{-5}
Iron	198 x 10^{-5}	18 x 10^{-5}
Invar	40 x 10^{-5}	-
Brass	340 x 10^{-5}	57 x 10^{-5}
Epoxy/ Fiberglass	279 x 10^{-5}	47 x 10^{-5}
Titanium	134 x 10^{-5}	17 x 10^{-5}

Some Properties of Cryogenic Fluids

Fluid	Normal Boiling Point (K)	Density of Liquid at Normal Boiling Point (Kg/m^3)	Density of Gas at 1 Bar and 300 K (Kg/m^3)	(Volume of gas at 1 Bar, 300 K) / (Volume of liquid at normal boiling point)
Propane	231.07	580.89	1.80	323
Ethane	184.55	543.97	1.22	446
Xenon	165.04	2942.1	5.29	556
Krypton	119.77	2416.3	3.40	711
Methane	111.63	422.42	0.64	660
Argon	87.28	1395.5	1.62	861
Oxygen	90.19	1142.2	1.3	879
Nitrogen	77.2	807.3	1.12	720
Neon	27.09	1205.2	0.81	1488
Hydrogen (Para)	20.23	70.85	0.081	875
Helium	4.222	125.2	0.16	783

Cryogenic Fluid Properties

- Note the large volume ratio between liquid at boiling point and gas at room temperature and pressure

- This effect drives:

  - Oxygen Deficiency Hazards
  - Pressure safety issues in confined volumes
- Compare room temperature and pressure densities with that of dry air (1.2 kg/m^3) – Argon and Krypton will tend to accumulate in low spaces while helium and hydrogen will tend to accumulate under ceilings

  - Remember lesson learned from the Cleveland fire: in a spill or leak it may NOT be true that all the material goes to room temperature and pressure right away. Thus even Helium, Hydrogen and LNG may flow into low lying spaces

Cryogenic Fluid Properties

- Flammability Hazards
  - Hydrogen, Propane, Methane and Ethane are all flammable and require specialized handling and safety procedures (LNG is > 95% Methane along with some propane and ethane)
  - Note that hydrogen has 2 forms (ortha and para) with different properties.

Cryogenic Fluid Properties

- Oxygen is enables combustion and greatly increases fire risk and impact of resulting fires. It also requires special handling and procedures
- Due to the difference in boiling points between nitrogen and oxygen, air condensing on LN_2 cooled surfaces will be oxygen rich and thus present a hazard – care should be taken to either insulate lines to prevent condensation or to prevent the condensate from coming into contact with fuel and or ignition sources
  - A similar hazard can arise when using charcoal adsorbers cooled to liquid nitrogen temperatures in cryogenic plants or gas purification systems. If the flow stream moving through the adsorber has a sufficient oxygen content, the oxygen can condense of the charcoal thus mixing both a fuel (charcoal) and oxidizer (oxygen) together. Under these cases explosions can and have occurred. It may well be better to use noncombustible adsorbing material such as silica gel or molecule sieves in applications where significant oxygen content may be present.

Impact of Ionizing Radiation on LN_2

- Liquid nitrogen can contain oxygen impurities either through production or through condensation of air into the LN_2 during transport and use.

- Ionizing radiation can convert some of this oxygen (O_2) into ozone (O_3) The ozone can then convert back to O_2 releasing enough energy to cause an explosion. Explosions have been observed in LN_2 systems exposed to large amounts of ionizing radiation. Examples have been observed with gamma rays, neutrons and high energy electrons.

- The details of this phenomena are not completely understood and there may also be some additional contributions due to the formation of various nitrogen-oxygen compounds in the irradiated system. The radiation dose required for this phenomenon to occur is generally quite high, but there have been cases reported at lower doses as well

- Given the uncertainty surrounding this hazard, it is best not to subject LN_2 systems (and also liquid oxygen or liquid air systems) to ionizing radiation. At the very least, this hazard must be considered and the risk determined prior to operation.

- An additional reason for avoiding the use of nitrogen in accelerator tunnels (where it might be subject to ionizing radiation) is the oxygen deficiency hazard posed by the nitrogen.

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General Cryogenic Safety

Cryogenic Hazards

- In addition to the very important hazards of Oxygen Deficiency, Pressure Safety, flammability and use of liquid oxygen; hazards in cryogenic facilities are related to the extreme cold of the cryogenic liquids and gases.
- This extreme cold can result in eye injury and blindness and tissue damage “burns”
- The solution for safe work is awareness of this hazard and use of the appropriate Personal Protective Equipment (PPE)
- Additionally, many cryogenic systems operate under pressure or can generate pressure to heat leaks and evaporation of cryogens. This can cause risks during handling and cryogenic transfer operations

Personal Protective Equipment (PPE) for Cryogenic Operations

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- PPE requirements may vary between institutions but the recommended minimum set of PPE is:
  - Eye protection via safety goggles or safety glasses with side shields
  - Face protection via face shield (A face shield does not provide eye protection, safety glasses still need to be worn under it)
  - Easily removable insulated gloves appropriate for cryogenics (NOT clean room gloves, cotton or wool gloves which can wick the cryogenic liquid to your skin and hold it there - increasing damage)
  - An insulated apron to protect against splashing
  - Long pants without cuffs that cover the tops of your shoes
  - Closed toed shoes

PPE for Cryogenic Operations

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- This PPE should be worn whenever handling open containers of cryogens, transferring cryogens between containers (including filling LN_2 dewars) transferring cryogens from a liquid trailer, and pulling or inserting bayonet connections (or U-tubes)
- Operation of sealed cryogenic systems such as those cooled by cryogenic plants may not require this level of PPE. However, if maintenance activities take place that could expose you to cryogenic temperatures then the PPE should be worn.
    - Perform a hazard analysis for all tasks to see if additional PPE is required
- ALWAYS wearing eye protection in a cryogenics facility is a good practice and required in many institutions.

PPE Examples

From TempShield   http://www.tempshield.com

Additional Comments on General Cryogenic Safety

- Keep in mind that materials that have been splashed by cryogenic liquids or exposed to cold venting vapor may be cooled down to the extent that they now can cause tissue damage
  - Be aware when touching these (Gloves)
  - Design pressure relief systems and vents so that cold vapor is not directed onto other materials or into places where personnel are likely to be (e.g. transport aisles)
- Do not walk into visible vapor clouds. In addition a very real Oxygen Deficiency Hazard, the vapor might be cold enough to cause tissue or eye damage
- Do not become complacent when working with LN_2 Even small amounts can cause eye or tissue damage.
  - Can we please stop with LN_2 cocktails ?

Additional Comments on General Cryogenic Safety

- Ensure that all cryogenic systems are depressurized before:
  - Pulling U-tubes or bayonets
  - Opening valves, flanges or container lids
  - Connecting or disconnecting hoses or piping
- Note that small unavoidable heat leaks will result in pressure increase due to evaporation in any sealed system containing liquid cryogens or even cold gases.
  - Therefore Never place cryogenic fluid or cold gases into any closed container not specifically designed for them (household Thermos bottles are particularly dangerous)
  - Never defeat or bypass pressure safety relief systems.
  - Insertion of warm line or U-tubes into cryogens (e.g. LN_2) will cause rapid boiling, pressure rise and /or venting. Always allow for this hazard in the operation.

Summary - Best Practices

1. Only use materials at cryogenic temperatures that have been proven to operate at these temperatures
2. Always conduct an Oxygen Deficiency Hazard analysis when using cryogenic fluids or inert gases no matter how small the quantity involved.
3. Always take into account the volume expansion and subsequent pressure rise associated with cryogenic fluids. Design in appropriate pressure relief systems
4. Always wear appropriate personal protection equipment, including eye protection, when handling cryogenic fluids no matter how small the amount
5. Ensure that relief valves and vent lines do not direct the flow of cold gas towards people or towards materials not designed for cryogenic temperature use.
6. Take into account the flammability hazards associated with Hydrogen, LNG and other hydrocarbons.
7. Take into account the unique hazards associated with oxygen

Summary - Best Practices

8. Insulate lines and cold surfaces so that air does not condense on them. If this is not possible, install drip trays or other approaches to safely manage the resultant oxygen rich condensate.

9. Design for the significant thermal contraction that occurs upon cooling many materials down to cryogenic temperatures.

10. Be aware of and plan for the relative densities of gases used in cryogenics and their relationship to the density of air. Take into account the possibility that vented gases or spilled fluids may not warm up to 300 K immediately.

11. Ensure that cryogenic systems are depressurized before carrying out activities such as: pulling of bayonets and U-tubes, opening valves, flanges or container lids and connecting or disconnecting piping or hoses

12. Only use approved containers for storage and transport of cryogenic liquids and cold gases.

13. Never defeat or bypass pressure relief systems

Irradiation of LN_2 Hazards References

G. W. Chen, R. G. Struss, "On the Cause of Explosions in Reactor Cryostats for Liquid Nitrogen", *Cryogenics*, April 1969

"Explosion Risk in Liquid Nitrogen" ATLAS AOS No 12, CERN (2013).

Oxygen Deficiency Hazards

Example Accident

In March of 1981, three technicians working at the Kennedy Space Center entered a compartment in the aft section of the space shuttle Columbia that had been purged with gaseous nitrogen. Due to a combination of poor communication and inadequate procedures, the technicians were unaware of the presence of an oxygen deficient environment in the compartment. All three technicians collapsed immediately. Two other workers entering the compartment in an attempt to rescue the first three also collapsed. Two of the three initial technicians died and one of the collapsed rescuers died several years later due to complications from the accident

This illustrates several typical features of ODH accidents:

Rapidity of event

Presence of fatalities

Multiple fatalities

Impact on would be rescuers

What are
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
- 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
- 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

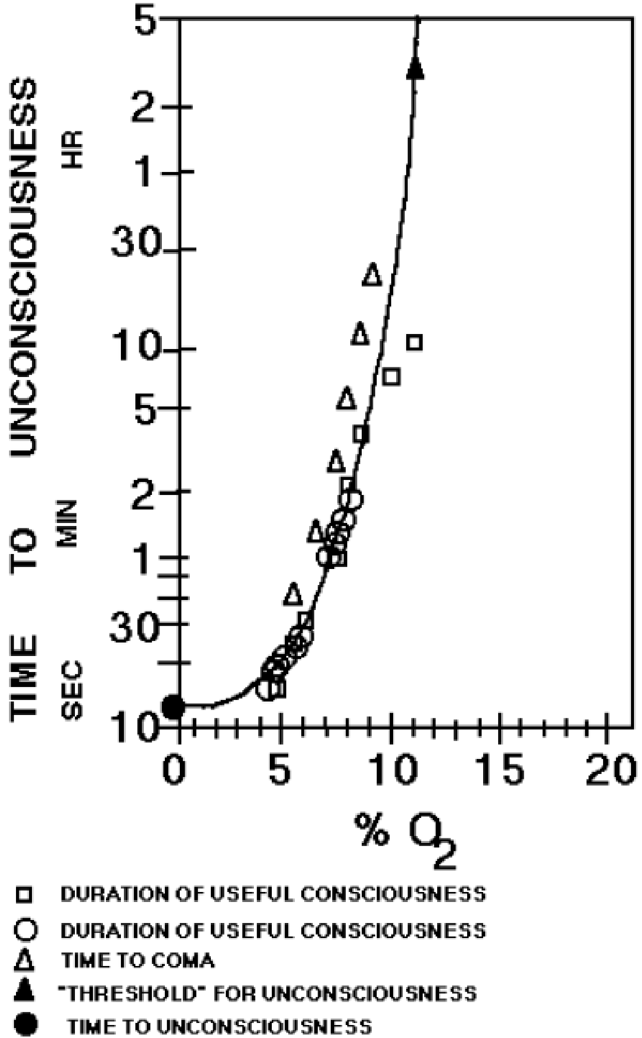
Recall Volume Changes for Cryogenic Fluids from Normal Boiling Point to 300 K & 1 Bar

Fluid	(Volume of gas at 1 Bar, 300 K) / (Volume of liquid at normal boiling point)
Propane	323
Ethane	446
Xenon	556
Krypton	711
Methane	660
Argon	861
Oxygen	879
Nitrogen	720
Neon	1488
Hydrogen (Para)	875
Helium	783

Effects 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

ODH Safety Basics

Understand the problem

Determine level of 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 laboratories (ESS,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

Apply mitigations to reduce the risk

Have a plan to respond to emergencies

<u>ALL users of cryogenic fluids no matter how small should analyze their risk and consider mitigations</u>

- At a minimum, everyone should be trained to understand the hazard

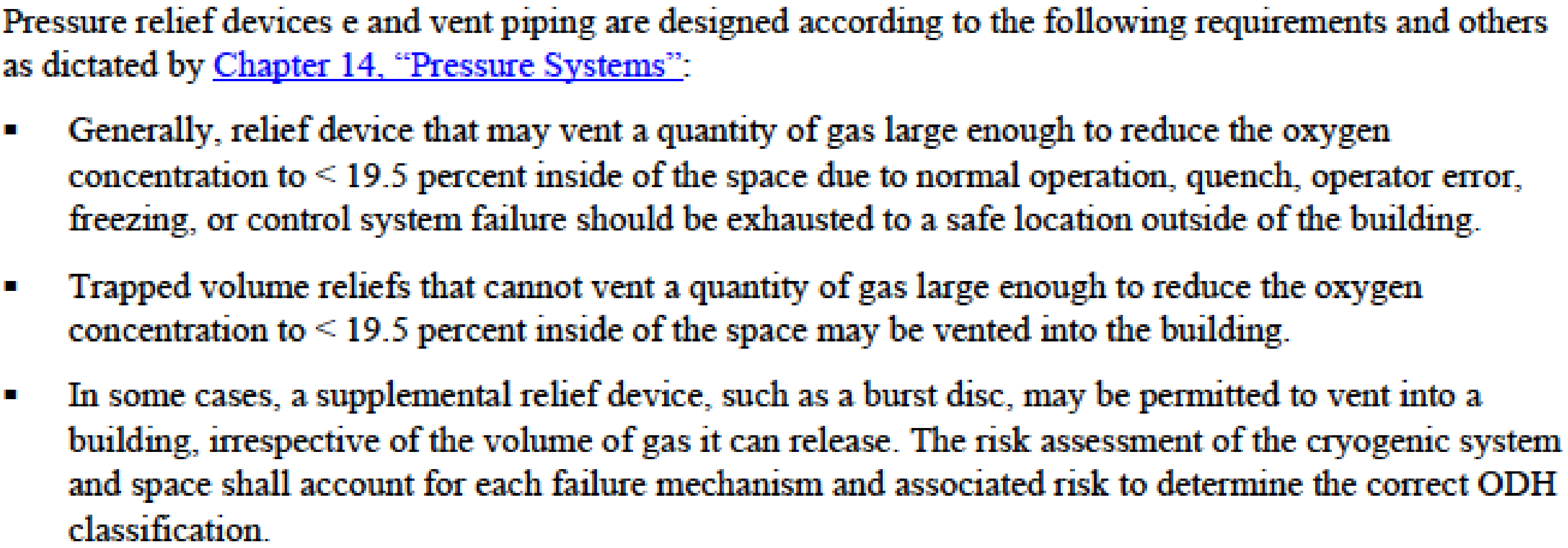
ODH Mitigations

- Best solution: Eliminate the hazard by design choices
  - Reduce inventory of cryogenic fluids & compressed gases
    - Use minimum amounts of cryogens or oxygen displacing gas
    - Restricted Flow Orifaces (RFOs) passive devices used in conjunction with compressed gas systems to reduce the amount of oxygen displacing gas that can enter an area.
  - Do not conduct cryogenic activities in small spaces
  - Do not transport cryogens in closed vehicles or in elevators with people
  - Do not use LN_2 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

If at all possible vent relief devices outside of buildings

An example policy from SLAC is shown below



Pressure relief devices e and vent piping are designed according to the following requirements and others as dictated by Chapter 14, "Pressure Systems":

- Generally, relief device that may vent a quantity of gas large enough to reduce the oxygen concentration to < 19.5 percent inside of the space due to normal operation, quench, operator error, freezing, or control system failure should be exhausted to a safe location outside of the building.
- Trapped volume reliefs that cannot vent a quantity of gas large enough to reduce the oxygen concentration to < 19.5 percent inside of the space may be vented into the building.
- In some cases, a supplemental relief device, such as a burst disc, may be permitted to vent into a building, irrespective of the volume of gas it can release. The risk assessment of the cryogenic system and space shall account for each failure mechanism and associated risk to determine the correct ODH classification.

Note that this last point can be challenging in tunnel environments

ODH Mitigations

- Work Rules
  - Prohibit activities that increase risk of an accident
    - ESS & CERN: No tunnel entry during cool down and warm up of accelerator
  - Two Person Rule
  - Three Person Rule (unexposed observer)
- Use of lintels and vents to keep helium away from escape routes
  - For example at Jlab

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 ODH
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 Risk Analysis

In many labs e.g. ESS, SLAC, CERN, Fermilab this is done in two steps:

First: a simple calculation that determines if there is any problem at all. This approach compares the volume of the space containing the cryogen with the volume occupied by the inert gas if the entire cryogenic inventory is released, warmed up to 300 K and 1 Bar and uniformly mixed. The resulting oxygen concentration (C) in percent is given by:

$$C = \frac{21(V_R - V_C)}{V_R}$$

Where V_R is the volume of the space and V_C is the volume of the inert gas at 300 K and 1 Bar

<u>Note: This calculation assumes 1 exchange of the room air per hour.</u>

ODH Risk Analysis

In the case where the inert gas is coming from outside the space, such as in the case of a helium compressor, the oxygen concentration is

$$C = \frac{21(V_R - Q)}{V_R}$$

Where V_R is the volume of the room and Q is the volumetric flow rate of the inert gas at room temperature and pressure. This calculation assumes 1 exchange of the room air per hour.

If either of these oxygen concentrations are less than 19.5% under normal operating conditions or less than 18% under abnormal conditions then a more sophisticated risk analysis is required

Even the simple analysis above (which should be done whenever inert gases or cryogens are used – no matter how small the amount) should be reviewed by an independent analyst and formally documented.

Keep in mind the underlying assumption of uniform mixing. Be aware of helium being trapped at a high level, argon gas concentrated in pits or trenches and the possible effect of gas colder than 300 K

Step 2: A More Detailed Risk Assessment

This is done by calculating a probable fatality rate (without mitigations) for each possible failure in the system being studied

These are then summed up for a total fatality rate which gives an ODH class

Each ODH class has a set of predefined mitigations

- Required mitigations by class may vary from institution to institution

A key component of this approach is the review of the calculations and mitigations by others (for example an ODH or cryogenic safety committee)

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

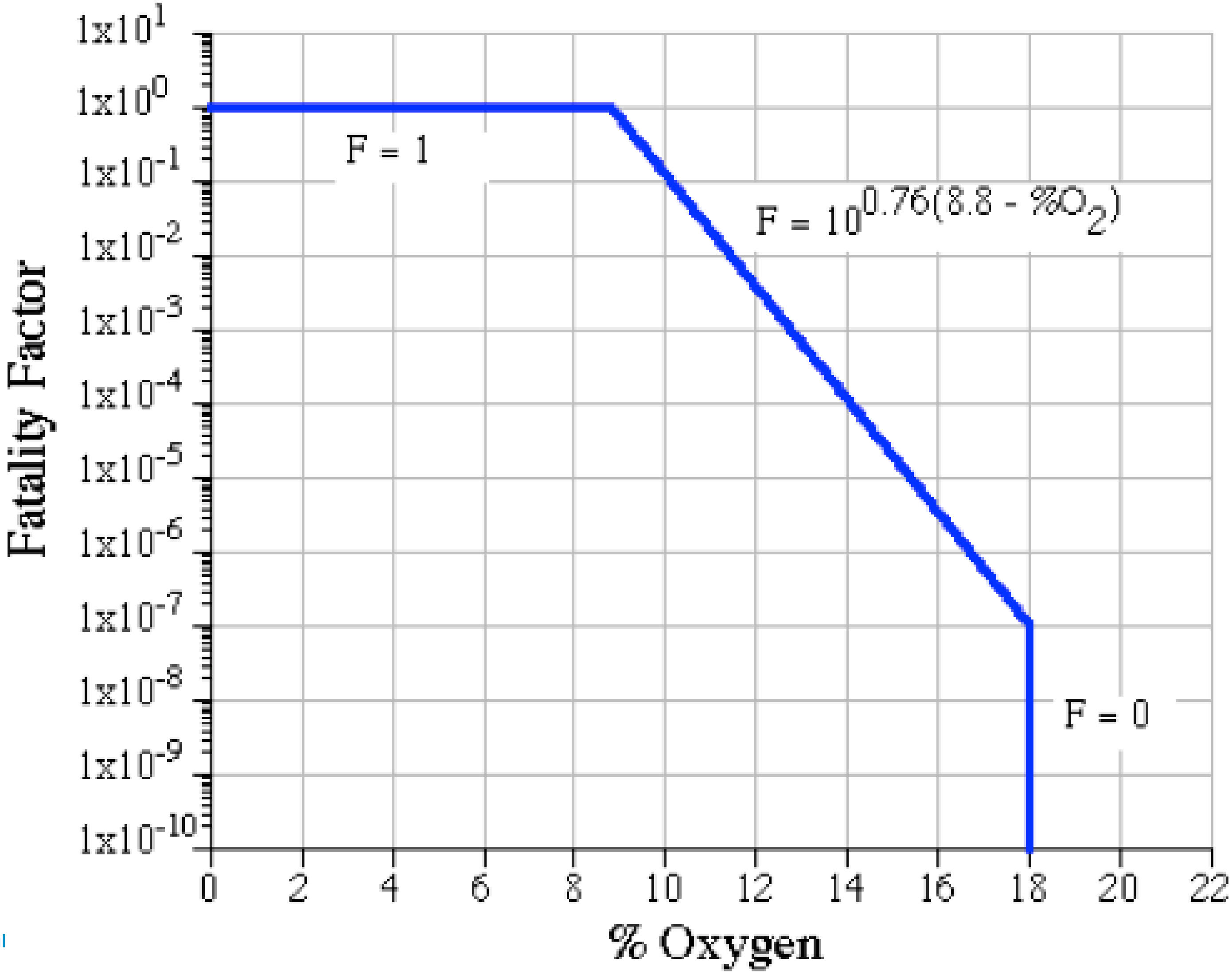
ODH Fatality Rates

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)

This is the same for ESS, SLAC and Fermilab



Note below 8.8% the fatality factor is taken to be 1 as this is the point at which useful consciousness is 1 minute

ODH classes at ESS

ODH Class	$[\Phi]$ (hr^{-1})
0	$\leq 10^{-7}$
1	$>10^{-7}$ …but… $\leq 10^{-5}$
2	$>10^{-5}$ …but… $\leq 10^{-3}$
Forbidden area Not permitted at ESS	$>10^{-3}$

Note these are fatality rates without any mitigations

Once the mitigations are applied, the fatality rate should be class 0 or better

ESS Mitigations vs. ODH Class

(note these are minimum mitigations, additional ones may be required by the safety committee)

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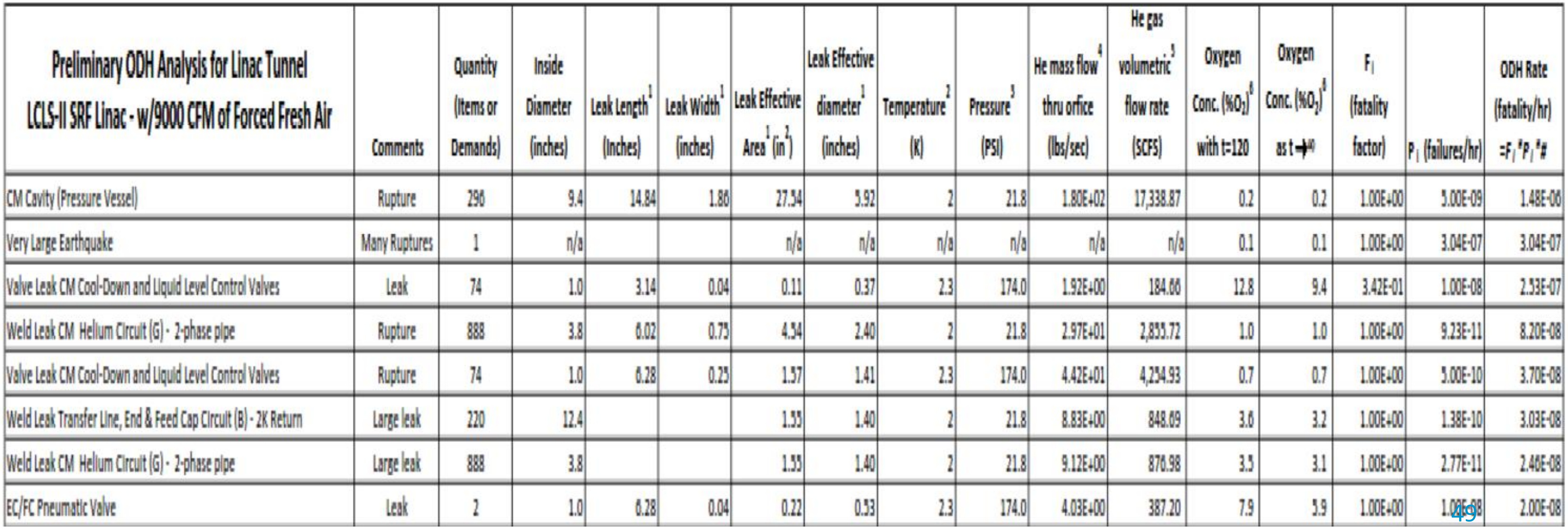
ODH Class	0	1	2
Technical Safety measures			
Warning signs	X	X	X
Ventilation		*	*
Area (fixed) Oxygen Monitoring	*	X	X
Organizational Safety measures			
Medical approval as ODH qualified		*	*
ODH training (e-learning)	X	X	X
Personal oxygen monitor		X	X
Self-rescue mask		*	*
Presence of minimum 2 persons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

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

Example Calculation

“ LINAC Coherent Light Source II (LCLS-II) Project Preliminary Oxygen Deficiency Hazard Analyses” - LCLSII-1.1-PM-0349-R1 (see handouts)

- **This is a very detailed analysis using the SLAC procedures and well worth using as a model**
- **Final result was that the Linac housing (tunnel), Gallery and Cryogenics building were rated as Class 1**
- **Work restrictions on entry into tunnel during cool down and warm up.**



Preliminary ODH Analysis for Linac Tunnel LCLS-II SRF Linac - w/9000 CFM of Forced Fresh Air	Comments	Quantity (Items or Demands)	Inside Diameter (inches)	Leak Length[1] (Inches)	Leak Width[1] (inches)	Leak Effective Area[1] (in^2)	Leak Effective diameter[1] (inches)	Temperature[2] (K)	Pressure[3] (PSI)	He mass flow[4] thru orfice (lbs/sec)	He gas volumetric[5] flow rate (SCFS)	Oxygen Conc. (%O$_2$)[6] with t=120	Oxygen Conc. (%O$_2$)[6] as t→∞	F$_i$ (fatality factor)	P$_i$ (failures/hr)	ODH Rate (fatality/hr) =F$_i$*P$_i$*#
CM Cavity (Pressure Vessel)	Rupture	296	9.4	14.84	1.86	27.54	5.92	2	21.8	1.80E+02	17,338.87	0.2	0.2	1.00E+00	5.00E-09	1.48E-06
Very Large Earthquake	Many Ruptures	1	n/a			n/a	n/a	n/a	n/a	n/a	n/a	0.1	0.1	1.00E+00	3.04E-07	3.04E-07
Valve Leak CM Cool-Down and Liquid Level Control Valves	Leak	74	1.0	3.14	0.04	0.11	0.37	2.3	174.0	1.92E+00	184.66	12.8	9.4	3.42E-01	1.00E-08	2.53E-07
Weld Leak CM Helium Circuit (G) - 2-phase pipe	Rupture	888	3.8	6.02	0.75	4.54	2.40	2	21.8	2.97E+01	2,855.72	1.0	1.0	1.00E+00	9.23E-11	8.20E-08
Valve Leak CM Cool-Down and Liquid Level Control Valves	Rupture	74	1.0	6.28	0.25	1.57	1.41	2.3	174.0	4.42E+01	4,254.93	0.7	0.7	1.00E+00	5.00E-10	3.70E-08
Weld Leak Transfer Line, End & Feed Cap Circuit (B) - 2K Return	Large leak	220	12.4			1.55	1.40	2	21.8	8.83E+00	848.69	3.6	3.2	1.00E+00	1.38E-10	3.03E-08
Weld Leak CM Helium Circuit (G) - 2-phase pipe	Large leak	888	3.8			1.55	1.40	2	21.8	9.12E+00	876.98	3.5	3.1	1.00E+00	2.77E-11	2.46E-08
EC/FC Pneumatic Valve	Leak	2	1.0	6.28	0.04	0.22	0.53	2.3	174.0	4.03E+00	387.20	7.9	5.9	1.00E+00	1.00E-08	2.00E-08

ODH and Visitors

Visitors and occasional staff (guards, custodial, delivery, visiting contractors etc.) should always be trained in ODH hazards and procedures or escorted by trained staff

Summary

Oxygen Deficiency Hazards are a significant threat and can lead to fatal accidents even with small amounts of cryogens or oxygen displacing gases

ODH can, however, be properly managed to allow safe work in cryogenic facilities

Significant experience with ODH safety exists and resources exist at labs such as ESS, SLAC, Fermilab, Jlab etc. (see handouts)

<u>Do not become complacent!</u>

Best Practices

1. Always evaluate the risk of an oxygen deficiency hazard whenever dealing with cryogenic fluids or compressed gases, no matter how small the amount.

2. Develop a well understood and documented approach to evaluating and mitigating oxygen deficiency hazards.

3. Consider at the beginning of the system design, choices that minimize or eliminate oxygen deficiency hazards. These may include: reducing the cryogenic inventory, limiting the amount of inventory that can be released in an accident, venting relief systems outdoors, maximizing interior space in which cryogenic systems are contained and designing tunnels with sufficient exits and ventilation to reduce ODH risk.

4. Have all ODH analyses independently reviewed.

5. Ensure that anyone (including visitors, contractors, maintenance & service staff) working in an ODH area is aware of the hazard and properly trained.

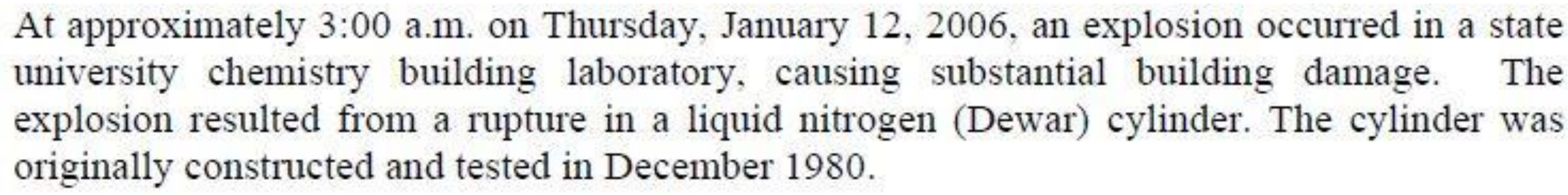
6. Immediately leave an area in the event of an ODH alarm or other indication of a leak such as a vapor cloud. Do not walk through vapor clouds while exiting.

7. Never enter an area in which an ODH alarm has sounded or that is otherwise thought to be oxygen deficient unless you have been properly trained and equipped for such entries.

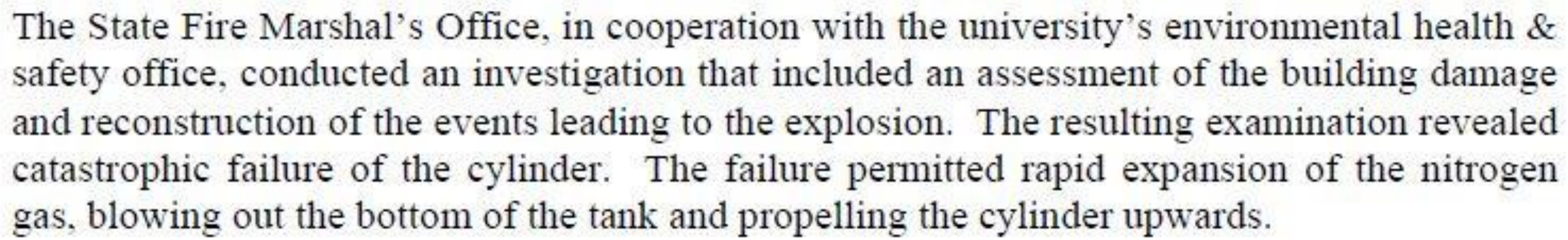
8. Do not transport even small amounts of cryogenic fluids inside cars or elevators.

Introduction to Pressure Safety

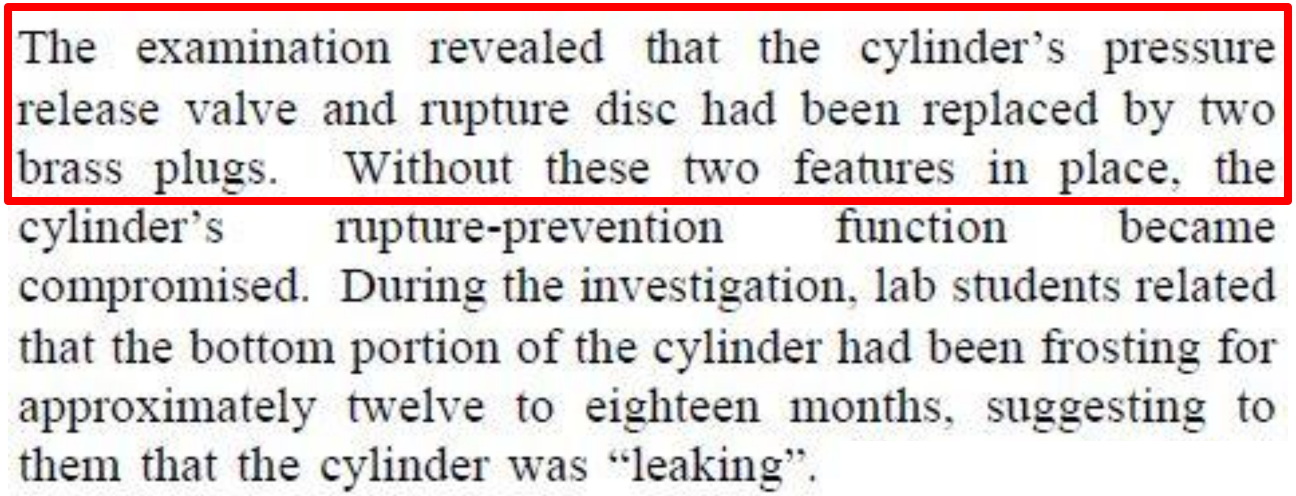
Example accident: LN2 dewar explosion, for the report, see http://www.tdi.texas.gov/fire/documents/fmred022206.pdf



At approximately 3:00 a.m. on Thursday, January 12, 2006, an explosion occurred in a state university chemistry building laboratory, causing substantial building damage. The explosion resulted from a rupture in a liquid nitrogen (Dewar) cylinder. The cylinder was originally constructed and tested in December 1980.



The State Fire Marshal's Office, in cooperation with the university's environmental health & safety office, conducted an investigation that included an assessment of the building damage and reconstruction of the events leading to the explosion. The resulting examination revealed catastrophic failure of the cylinder. The failure permitted rapid expansion of the nitrogen gas, blowing out the bottom of the tank and propelling the cylinder upwards.



The examination revealed that the cylinder's pressure release valve and rupture disc had been replaced by two brass plugs. Without these two features in place, the cylinder's rupture-prevention function became compromised. During the investigation, lab students related that the bottom portion of the cylinder had been frosting for approximately twelve to eighteen months, suggesting to them that the cylinder was "leaking".

State Fire Marshal's Alert

February 22, 2006

University Campus Liquid Nitrogen Cylinder Explosion

Incident Specifics

Figure 1 -Effect of Explosion on Dewar Cylinder Compared to unaffected cylinder

Figure 2 - Hallway Outside Laboratory Showing Explosion Damage

Figure 3 - Inside the Laboratory after Explosion

Over Pressurization Hazards

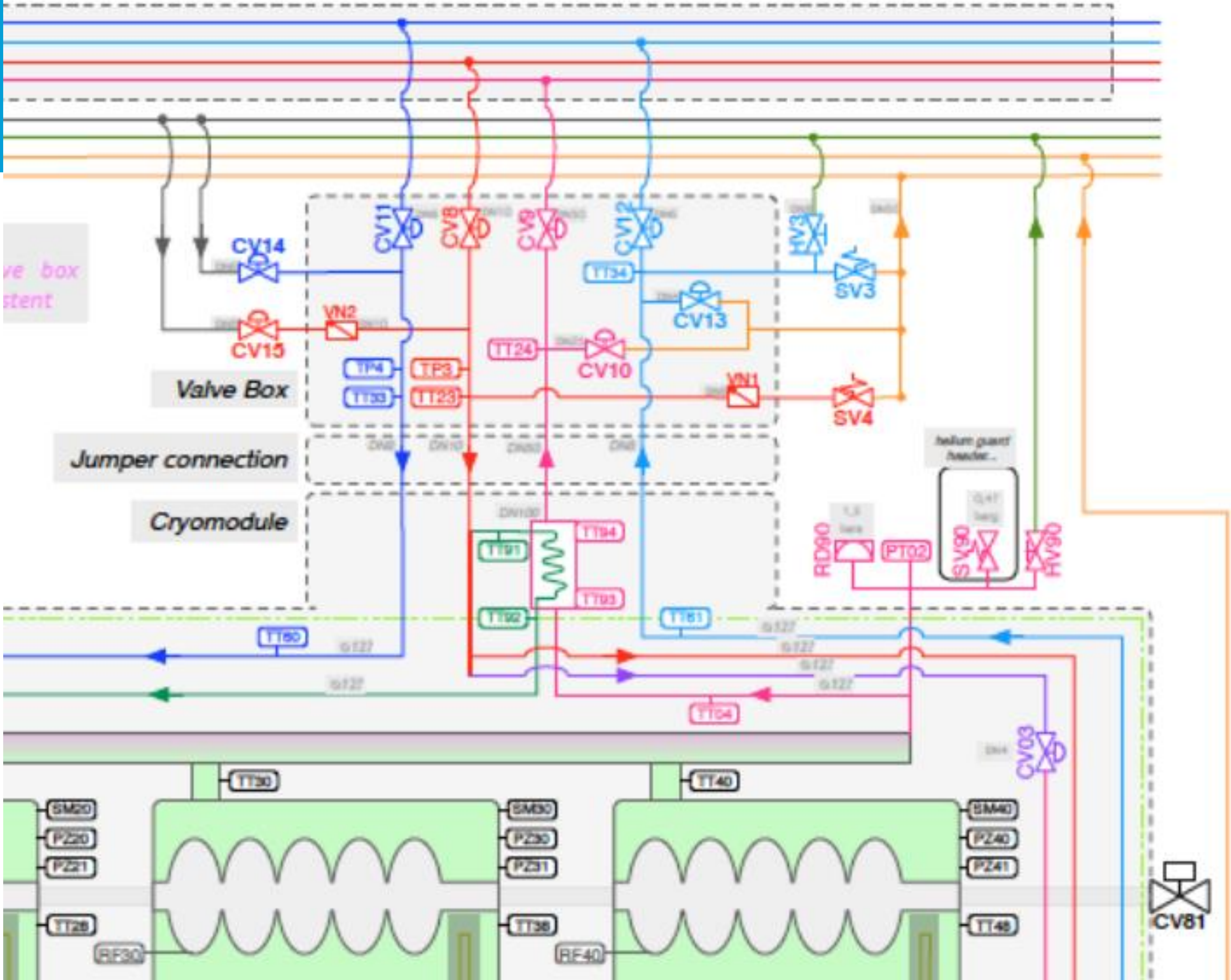
- A principal hazard that results from the large volume expansion that occurs when a cryogenic liquid is converted to 300 K gas
- As a result large pressure rises are possible
- This could easily result in material failures, and explosive bursting

Recall Volume Changes for Cryogenic Fluids from Normal Boiling Point to 300 K & 1 Bar

Fluid	(Volume of gas at 1 Bar, 300 K) / (Volume of liquid at normal boiling point)
Propane	323
Ethane	446
Xenon	556
Krypton	711
Methane	660
Argon	861
Oxygen	879
Nitrogen	720
Neon	1488
Hydrogen (Para)	875
Helium	783

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)


ve box
stent
Valve Box
Jumper connection
Cryomodule
CV14
CV15
VN2
CV11
CV8
CV9
CV12
HV3
SV3
TT34
CV13
TT24
CV10
TP4
TP3
TT33
TT23
VN1
SV4
helium guard header..
RD90
PT02
SV90
HV90
TT94
TT91
TT93
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TT81
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SM20
PZ20
PZ21
TT28
RF30
SM30
PZ30
PZ31
TT38
RF40
SM40
PZ40
PZ41
TT48
CV81

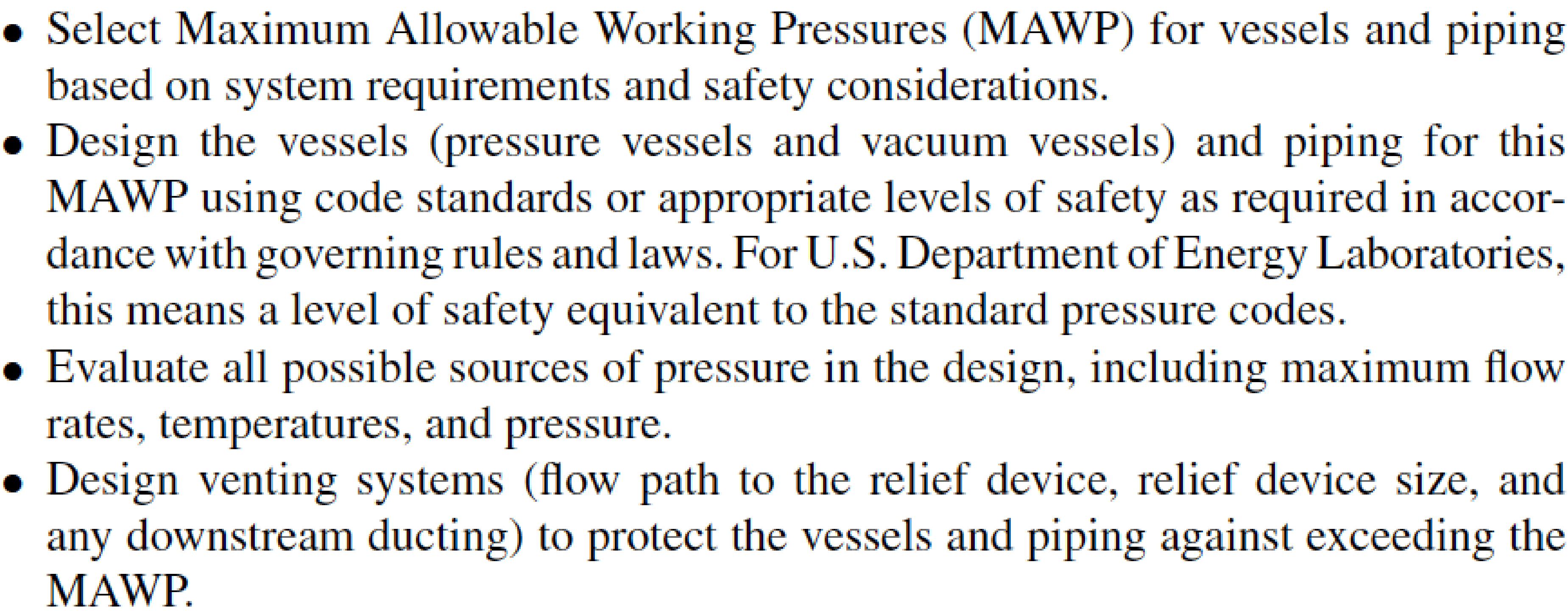
Pressure Relief Systems

- The pressure relief of a cryogenic system, particularly in worst case scenarios can be very dynamic with rapidly changing temperatures, pressures, flows and phases.
- Sizing of relief valves and associated systems may be proscribed by applicable pressure vessel codes (PED, ASME etc)
- Third party inspection and approval is frequently required.
- In cryogenic systems the worst case scenario is the breaking of a vacuum system. The in rushing air condenses on the cold cryogenic surfaces and deposits heat into the the cryogenic fluid causing rapid boiling and expansion.
- Never place shut off valves between systems and relief valves. In some cases 3 way valves are used with parallel relief valves to allow maintenance

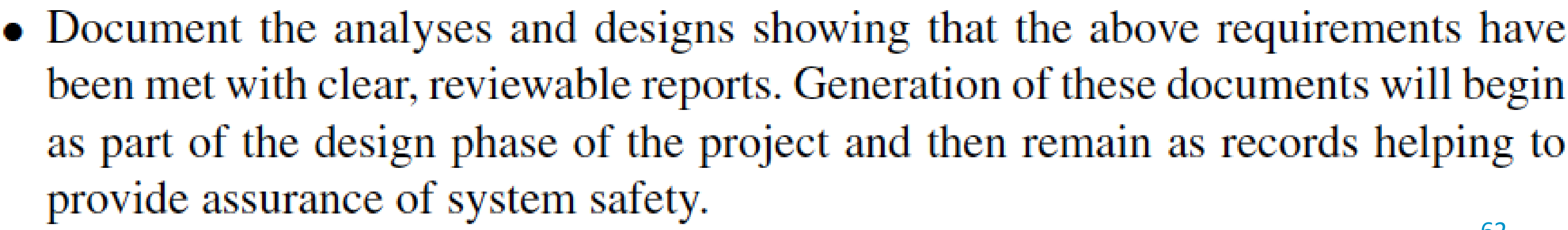
Pressure Relief Systems

- Cryogenic systems should be vented into either a recovery system or into the outside air not into tunnels or buildings
- Take care that collection headers and recovery systems do not result in the pressure at the relief valves being too high when the system is venting
- Never bypass or disable pressure reliefs
- Much more detail given in supplemental slides by Tom Peterson (SLAC)

Pressure Safety Best Practices



- Select Maximum Allowable Working Pressures (MAWP) for vessels and piping based on system requirements and safety considerations.
- Design the vessels (pressure vessels and vacuum vessels) and piping for this MAWP using code standards or appropriate levels of safety as required in accordance with governing rules and laws. For U.S. Department of Energy Laboratories, this means a level of safety equivalent to the standard pressure codes.
- Evaluate all possible sources of pressure in the design, including maximum flow rates, temperatures, and pressure.
- Design venting systems (flow path to the relief device, relief device size, and any downstream ducting) to protect the vessels and piping against exceeding the MAWP.



- Document the analyses and designs showing that the above requirements have been met with clear, reviewable reports. Generation of these documents will begin as part of the design phase of the project and then remain as records helping to provide assurance of system safety.