Short Course on Cryogenic Safety

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May 10, 2006
Short Course Agenda

• Part 1 8:45 – 10:30AM
  – Introduction
    • Safety and Cryogenic Fluids
    • Cryogens of Interest to SLAC
  – General Safety Topics
    • Physiological Hazards
    • Materials and Construction
    • Over-pressurization, Explosive and Flammability Hazards
    • Personnel and Operational Awareness
  – Material Safety Data Sheets

• Part 2 10:45 – Noon
  – Cryogenic Design and Safety Equipment
    • Design Considerations
    • Cryogenic Relief Valves
    • Burst Discs
    • Venting of Facilities and Systems
    • System Monitoring
  – Problems of Interest
  – Summary
Short Course on Cryogenic Safety
Part 1. – Introduction
• Safety and Cryogenic Fluids
• Cryogens of Interest to SLAC
Cryogenic Storage and Cooling Systems

• Cryogens require specialized storage containers to maintain any kind of shelf life (system boil-off time > minutes)
  – Commonly known as “Dewars”!
  – Storage containers range in size from 1 Liter to 42,000,000 gallons
  – Cooling systems, such as the ones in use at SLAC (LN$_2$, LHe)

• Economics and Safety determine best system design
  – Rate Loss (Heat leak)
  – Weight
  – Materials of Construction (System Compatibility)
  – Insulation System (Dependent upon life requirements)
  – Specialized Requirements (dynamic environments, etc.)

• SLACs use of the nitrogen, carbon dioxide and helium also brings in the need for some amount of knowledge on oxygen and its unique requirements

• In this course we will not deal a lot with carbon dioxide, most everything that relates to cryogenic nitrogen will cover C0$_2$
  – Freezing point at about 216 K somewhat the conventional number of 188K, not considered a cryogenic fluid

5/30/2006
BaBar Refrigerator & Solenoid

* Courtesy of John Weisend
Cryogenic Storage and Cooling Systems

- Many standard designs are available through a variety of suppliers and manufacturers; established international codes and regulations have worked out.
- ASME Boiler and Pressure Vessel Code, Section VIII and is mandatory for most experimental equipment design and construction
- Compressed Gas Association (CGA) has a number pamphlets published dealing with handling of cryogenics
  - P-1 Safe Handling of Compressed Gases in Containers
  - S-1.1 Pressure Relief Device Standards Part 1 (circular cross-sectional storage units)
  - S-1.2 Pressure Relief Device Standards Part 2 (cargo and transportable)
  - S-1.3 Pressure Relief Device Standards Part 3 (permanently mounted units)
  - ASME B31.1 Power Piping and ASME B31.3 Chemical Plant and Petroleum Piping (design and inspection of welded joints)
- Other regulatory documents that I recommend
  - CGA G-4.1 Cleaning Equipment for Oxygen Service
  - 29 CFR 1910.104 Oxygen (OSHA standard)
Short Course on Cryogenic Safety
Part 1. – General Safety Topics

• Physiological Hazards
  • Materials and Construction
• Over-pressurization, Explosive and Flammability Hazards
  • Personnel and Operational Awareness
Physiological Hazards

- Contact Burns/Frostbite
- Asphyxiation/Toxicity
  - Hypothermia
Contact Burns/Frost Bite: What are they?

- **Contact Burn** – exposure of the skin to low temperatures.
  - Similar to heat burns; can locally freeze and tear or remove skin.
  - Due to decrease in feeling, can easily lead to Frost Bite!

- **Frost Bite** – freezing of skin and body parts due to exposure of low temperatures.
  - Can lead to permanent damage and discoloration up to loss of limb.
  - Prolonged exposure of cold vapour or gas can damage lungs and the eyes.
  - Exposure time on the order of seconds, not minutes!!

- Due to the nature of cryogens low viscous nature, will penetrate woven and other porous clothing materials much faster than water!
Contact Burns/Frost Bite: How to Avoid?

- Personnel training is critical to personnel safety
  - An organized well thought-out safety training program will significantly reduce personnel injuries in this area
- Minimize exposure to operation
- If you need to be there, understand where the risks are. Vent locations, cold equipment, etc.
- Wear proper protective clothing
  - Non-absorbent loose fitting gloves; eye protection, non-flammable cover-alls, proper footwear
- Never go alone!!
- Make someone aware of what you doing, who is not with you.
- Watch out for problems and if you don’t understand; STAND DOWN!
Contact Burns/Frost Bite: What about clothing?

- Not only are safety glasses or goggles required but face shields are also required for systems under pressure and handling/venting cryogens.

- Recommend loose fitting, grease-free leather gloves.

- Trousers should always been worn outside of boots or work shoes; no open or porous shoes are permitted.

- All clothing should be grease free.

- Clothing exposed to low temperature helium gas should be handled with care, potential oxygen build up in articles.
Contact Burns/Frost Bite: What to Do if Exposed?

• **Immediate first aid**
  – Remove from area, if required
  – Flush area with copious amounts of tepid water
  – Do not apply direct heat to area
  – Notify medical and arrange transport

• **While awaiting transport**
  – Loosen restrictive clothing
  – Continue flushing with water
  – Protect frozen/burned parts with sterile dry bondages
  – Do not smoke or drink, affects blood flow
  – Do not remove frozen clothing; massage or rub frozen parts; use safety showers or eye washes; or apply ointments
Asphyxiation/Toxicity: What is it?

• Displacement of oxygen in the air that you breathe by the cryogenic fluid vapour/gas release or venting could be an asphyxiation risk
  – Confined or minimal ventilation areas are biggest risk
  – However, all vapour clouds should be treated very carefully
  – Oxygen concentrations as low as 13% can be tolerated at 1 atmosphere

• Toxicity (poisoning) can cause damage and death if not adequately dealt with; appears not to be a problem at SLAC since the primary cryogens are non-toxic
  – Mentioned for completeness
Asphyxiation Oxygen Limits and Physical Reactions

**Sudden Asphyxia** – Inhalation of a gas containing practically no oxygen; unconsciousness is immediate (two breaths and out!)

**Gradual Asphyxia** – See Below!

<table>
<thead>
<tr>
<th>Percent Oxygen in Air</th>
<th>Physiological Reactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>12% - 14%</td>
<td>Respirations deeper, pulse up, coordination poor.</td>
</tr>
<tr>
<td>10% - 12%</td>
<td>Respiration fast and shallow, giddiness, poor judgment, lips blue.</td>
</tr>
<tr>
<td>8% - 10%</td>
<td>Nausea, vomiting, unconsciousness, ashen face.</td>
</tr>
<tr>
<td>6% - 8%</td>
<td>8 minutes, 100% fatal; 6 minutes, 50% fatal; 4-5 minutes, all recover with treatment.</td>
</tr>
<tr>
<td>4%</td>
<td>Coma in 40 seconds, convulsions, respiration ceases, death.</td>
</tr>
<tr>
<td>0%</td>
<td>Immediate unconsciousness without warning; may fall as if struck by a blow on the head. Death in 2-3 minutes if not resuscitated.</td>
</tr>
</tbody>
</table>
Asphyxiation/Toxicity: What is it avoided?

- Best option is to have a well ventilated area which sweeps and exchanges the air in the area of concern
  - HVAC design requirement, 1 – 2 volumes per minute
- Personnel training in confined space operations, use the Job Safety Analysis (JSA) approach!
- Use harnesses to allow you to be extracted
- Use air packs or lines until the environment is verified safe
- Allow work in teams with at least one member outside the confined space or area of concern to be the safety valve!
  - Communications within the entire team is critical to a safe operation
- Monitor environment for air composition
  - Portable and/or permanent oxygen monitors should be used
Asphyxiation/Toxicity: What to do if?

• Make sure that you are prepared
  – Safety extraction equipment is available and ready to use
  – Personnel are trained and certified for tasks
  – Have a plan (checklist) and use it!

• Remove any victim as quickly as practical to a normal atmosphere

• If not breathing, start artificial respiration immediately
  – Time is the killer here!

• Get into medical facility as soon as possible.
Hypothermia: What is it?

- Occurs when the body is not capable of maintaining its normal temperature.
  - Do you think in long duration operations with cryogenic fluids that this might be a problem?
  - Condition does affect personnel reaction time and mental awareness

- Precautions
  - Similar approach to Frost Bite however may add a layer or two of clothing to keep warm
  - Rotate crew members to keep from long term exposure

- What to do?
  - Get warm and do not re-engage until rested for at least 8 hours, if possible
Short Course on Cryogenic Safety
Part 1. – General Safety Topics

• Physiological Hazards
• Materials and Construction
• Over-pressurization, Explosive and Flammability Hazards
• Personnel and Operational Awareness
What materials are suitable for cryogenic systems and reduce the safety risks?

- Materials should remain ductile at the temperature of the cryogen used
  - Avoid bcc metals such as carbon steel or soft solder
- This are always trade-offs in material selection
  - Thermal expansion or contraction
  - Strength, yield and ultimate
  - Ductility, shock strength, fatigue life
  - Heat capacity
  - Thermal conductivity
  - Magnetic properties, etc
- Of particular interest in the safety arena are when and how might the material become unsafe?
Materials Can be Used to Your Advantage! Such As Ductile-Brittle Transitions

- Ductility of most metals decreases at low temperatures. Some undergo a rapid change over a narrow band.
- Transition temperature between ductile and brittle behavior is called NDT (Nil Ductility Transition) and is measurable.
- Charpy impact test is one of these tests
- NDT data is available for most materials but varies with specimen size, shape and test threshold.

<table>
<thead>
<tr>
<th>Temperature °F</th>
<th>Impact Value, ft-lb</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>-360</td>
<td>80</td>
<td>AISI 321 Stainless Steel</td>
</tr>
<tr>
<td>-260</td>
<td>67</td>
<td>5052 Aluminum</td>
</tr>
<tr>
<td>-160</td>
<td>59</td>
<td>67-33 Yellow Brass</td>
</tr>
<tr>
<td>-60</td>
<td>50</td>
<td>Be-Cu</td>
</tr>
<tr>
<td>40</td>
<td>30</td>
<td>AISI 4130 Steel</td>
</tr>
<tr>
<td>-218</td>
<td>4</td>
<td>50 Pb-50 Sn Soft Solder</td>
</tr>
<tr>
<td>-162</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>-107</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>-51</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>111</td>
<td>1</td>
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</tr>
<tr>
<td>166</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>222</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>277</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

5/30/2006
Thermal Stresses in Cryogenic Service Must be Accounted for in Design

• All materials contract when cooled from room temperature to cryogenic temperatures
• The expansion (and contraction) coefficient is a function of temperature but is typically 3 to 5 mm/m for common structural materials between room temperature and 77K
  – Little additional change occurs below 77K
• Joints and supports must be able to handle induced stresses and transitions between various materials, eg aluminum and stainless steel must be accounted for in the design
• An uneven cooldown will create large thermal stresses within a vessel
  – Pipeline example: 30 m stainless steel pipeline would contract 8.4 cm on cooldown to 77K
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Is SLAC at risk for an explosion?

• An explosion results from a sudden release of energy dissipated by air chock waves (and acceleration of shrapnel, thermal radiation, etc.) and causes a temporary over-pressurization

• Definitions of interest for explosions
  – A bursting explosion releases stored pressure energy without a chemical reaction – most likely risk at SLAC
  – A deflagration is a combustive explosion with a subsonic flame speed – least likely but possible at SLAC
  – A detonation is a combustive explosion with a supersonic flame speed
  – An enclosed space may turn deflagration into a detonation

• Mitigation is a usually a combination of design and appropriate safety devices to keep system from exploding
Over-pressurization needs to be addressed for all operations

• Example case for tank lock up
  - 1000 gal storage dewar
  - 1 percent per day boil off
  - Storage dewar is 70% full

• Parasitic heat expands liquid in tank
• Pressure rises at 0.36 psi/hour
• Once liquid fills ullage, pressure rises rapidly, 21 psi/hour

Quenching a large magnet with all its energy into a cryogenic cooling medium in the matter of milliseconds has the same effect only incredibly faster!
## Overpressurization Relationship to Blast Wave Dissipation Helps Make Point

<table>
<thead>
<tr>
<th>Blast Overpressure or Shrapnel Momentum</th>
<th>Structural or Biological Response to Blast Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 to 1 psig</td>
<td>Glass windows shatter</td>
</tr>
<tr>
<td>1 to 2 psig</td>
<td>Corrugated steel or aluminum paneling buckles</td>
</tr>
<tr>
<td>2 to 3 psig</td>
<td>Non-reinforced concrete or cinder-block walls shatter</td>
</tr>
<tr>
<td>5 psig</td>
<td>Eardrums rupture</td>
</tr>
<tr>
<td>7 to 8 psig</td>
<td>Non-reinforced brick walls shear and fall</td>
</tr>
<tr>
<td>15 psig</td>
<td>Lung damage</td>
</tr>
<tr>
<td>115 ft/sec for a 0.35-oz glass projectile or 10 ft/sec for a 10-lb masonry projectile</td>
<td>Projectile penetrates abdomen</td>
</tr>
<tr>
<td>10 ft/sec for a 160-lb man</td>
<td>Skull fracture from impact</td>
</tr>
</tbody>
</table>
Ok, but what does that mean to me?

<table>
<thead>
<tr>
<th>Distance (feet)</th>
<th>Overpressure (psig)</th>
<th>t1 (msec)</th>
<th>t2 (msec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>320</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>4</td>
<td>70</td>
<td>0.8</td>
<td>1.6</td>
</tr>
<tr>
<td>6</td>
<td>28</td>
<td>1.8</td>
<td>2.4</td>
</tr>
<tr>
<td>8</td>
<td>15</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>10</td>
<td>9.6</td>
<td>4.3</td>
<td>3.2</td>
</tr>
<tr>
<td>20</td>
<td>3.0</td>
<td>12</td>
<td>--</td>
</tr>
<tr>
<td>40</td>
<td>1.2</td>
<td>29</td>
<td>--</td>
</tr>
<tr>
<td>100</td>
<td>0.35</td>
<td>82</td>
<td>--</td>
</tr>
<tr>
<td>200</td>
<td>0.13</td>
<td>169</td>
<td>--</td>
</tr>
<tr>
<td>400</td>
<td>0.05</td>
<td>346</td>
<td>--</td>
</tr>
</tbody>
</table>

t1 is the blast wave arrival time

t2 is the time required for the overpressure to decay back to zero
Is fire a risk at SLAC due to cryogens?

- Obvious with gases such as hydrogen, oxygen, LNG and acetylene; but not used in normal operations at SLAC
- However, liquefied inert gases such as nitrogen and helium may condense oxygen out of the atmosphere, causing oxygen enrichment or entrapment in unsuspected places
- At temperatures < 82 K, metal surfaces will condense oxygen and form enriched air (50% O₂ and 50% N₂) to drip and pool on surfaces
  - Uninsulated pipelines provide this surface
  - Air boils at 78 K (at 1 atm of pressure) in a 6% O₂-94% N₂ vapor mixture, enriching the O₂ content
This is how enrichment works!

- Air condenses from an exposed LN$_2$ or cold GHe pipe is enriched to 50% O$_2$ (see chart)
- Falls/drips to ground and may flash off leaving O$_2$ rich local atmosphere; pool is ground gets cold enough; or drip onto flammable material
- Avoid this condition if at all possible
- If not, use drip pans to control where enriched air can go
Ok, so how do we prevent the possibility of fires in your cryogenic operations?

• As in all fire risks, you control the fire triangle you control the risk of fire

• In the case of SLAC, reduce the presence of the oxidizers to the minimum possible
  – Insulate exposed cryogenic transfer lines
  – Maintain good ventilation

• Eliminate all combustible materials
  – Good housekeeping is essential
  – Oxygen makes most everything burn so be careful

• Attempt to eliminate all ignition sources
  – Always assume they are present
  – No smoking, open flames, thermal ignition sources
  – Proper electrical techniques, lightning protection, static discharge controls
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Operational Hazards to Cryogenic Operations at SLAC

• Storage and tank failures – overpressurization
  – Must have relief devices and set at appropriate pressures
  – Tanks should be sized and spaced appropriately
  – Calibration and periodic maintenance is required!

• Process and procedures for spills, leakage and disposal
  – Venting paths established and verified open
  – Emergency equipment staged

• Transportation and transfer
  – Paths in and out are clear
  – Procedures established and dry-runs completed

• All venting should be controlled
  – Free venting of any cryogen should be eliminated or tightly controlled.
General Safety Check List

- Personnel training is critical in all aspects of cryogenic safety
- Always be safety conscious
- Be sure that all equipment is in good working order, including safety equipment
- Understand hazards to be faced in doing job
- Ensure adequate warning signs are posted
- Complete a JSA and review with team operations and procedures prior to doing job
- Always work as a team of two or more
- Know emergency steps and appendices
Contamination is Nothing to Mess With!

- Practice these essential elements of contamination control:
  - Initial system component disassembly and inspection
  - Cleaning of individual parts (I recommend all cryogenic parts be cleaning to a level equal to oxygen cleanliness as a minimum)
  - Visually inspect
  - Store and label components
  - Pressure and leak test systems
  - Verification of cleanliness by sampling
Short Course on Cryogenic Safety
Part 1. – Material Safety Data Sheets

• Nitrogen
• Helium