LOX, GOX, and Pressure Relief

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Ken McLeod
Joel Stoltzfus
NASA White Sands Test Facility
Disclaimer

• You are responsible for the application of the principles and information presented
• Neither NASA, Jacobs Sverdrup, Muniz Engineering Inc., nor the presenter assume any responsibility for your decisions
Why Consider Oxygen Pressure Relief?
Because fires occur

• In liquid oxygen systems
• In gaseous oxygen systems
• In less then 100% oxygen

And the consequences can be severe!
Aluminum O₂ regulator
Aluminum $O_2$ regulator
Apollo 204 Fire
Apollo 204 Fire
Dome-loaded Regulator Fire
Dortmund ASU Fire
Tank Cylinder Valve
Tank Cylinder Valve
O₂ Fires Occur Industry Wide

- Aerospace
- Industrial gases
- Medical
- Military
- Chemical processing
- Power generation
- Scuba diving
- Metals refining
- Emergency services
- Life support
Fire Triangle

System Components
- Adiabatic Compression
- Particle Impact
- Mechanical Impact
- Frictional Heating

Nonmetals
- Metals

Fuel
- Oxygen
- Air

Ignition
- Frictional Heating

Oxidizer
- Metals
- Nonmetals

Oxygen
- Air
The Oxygen System Dilemma

- Can’t remove a leg of the fire triangle
- No comprehensive equations
- No comprehensive modeling packages
- How do we manage the fire hazard?
Risk Management Approach

• Minimize ignition hazards
  – Identify and control ignition sources

• Maximize best materials
  – Ignition resistant
  – Flame propagation resistant
  – Low damage potential

• Utilize good practices
  – Test materials for which there is no data
  – Conduct hazard analysis on every design/change
Ignition Mechanisms
Adiabatic Compression Ignition

Heat generated when a gas is compressed from a low to a high pressure. Also called pneumatic impact or rapid pressurization

Characteristics
- High pressure ratio
- Rapid pressurization
  - Ball valves, cylinder valves, rupture discs
- Exposed nonmetal close to dead end
Adiabatic Compression Ignition

\[ \frac{T_f}{T_i} = \left[ \frac{P_f}{P_i} \right]^{(n-1)/n} \]

where \( n = \frac{C_p}{C_v} = 1.4 \) for oxygen

<table>
<thead>
<tr>
<th>Final Pressure (psia)</th>
<th>Pf/Pi</th>
<th>Final Temperature (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>6.8</td>
<td>453</td>
</tr>
<tr>
<td>500</td>
<td>34</td>
<td>986</td>
</tr>
<tr>
<td>1000</td>
<td>68</td>
<td>1303</td>
</tr>
<tr>
<td>2000</td>
<td>136</td>
<td>1688</td>
</tr>
<tr>
<td>4000</td>
<td>272</td>
<td>2158</td>
</tr>
</tbody>
</table>

ASTM G88, Table 1
Adiabatic Compression Ignition

- Most efficient direct igniter of nonmetals
- Will not ignite metals directly
- Examples
  - Regulators attached to cylinder valves
  - Components downstream of ball valves
  - Teflon-lined flex hose
**Particle Impact Ignition**

Heat generated when small particles strike a material with sufficient velocity to ignite the particle and/or the material

**Characteristics**

- Assume the presence of particles
- High velocity
- Impact point and residence time
- Flammable particle and target
Particle Impact Ignition
(continued)

- Most efficient direct igniter of metals
- Difficult to ignite nonmetals
- Particles can ignite at velocities of 150 ft/s
- Examples
  - First space shuttle flow control valve
Mechanical Impact Ignition

Single or repeated impacts on a material with sufficient force to ignite it

Characteristics

• Large impact or repeated impact loading
• Nonmetal at point of impact
Mechanical Impact Ignition
(continued)

Examples

- Poppet impact on valve or regulator seat
- Chatter on relief or check valve seat
- Special consideration in LOX
  - Hammer fitting on LOX tanker
  - Impacts on porous hydrocarbon materials or surfaces can be “explosion-like”
Galling and Friction Ignition

Heat generated by the rubbing of two or more parts together…

…like the Boy Scout fire-starting trick!

Characteristics

• Two or more rubbing surfaces
• High speed and high loads most severe
• Metal-to-metal contact most severe
  – Destroys protective oxide surfaces or coatings
  – Generates particulate
Flow Friction Ignition

Oxygen leaking across a polymer such that enough heat is generated within the polymer to cause ignition

Characteristics
• High pressure (>1000 psi)
• Leak or “weeping” flow
  – External leaks (seals)
  – Internal leaks (seats)
• Exposed nonmetal in flow path
  – Chafed or abraded surfaces increase risk
Flow Friction Ignition

Examples

- Dome-loaded regulator
- NASA MSFC chamber
Kindling Chain

Ignition of an easily ignited material that, in turn, may release sufficient heat to ignite larger, harder-to-ignite materials

Characteristics

• Active ignition mechanism (adiabatic compression, mechanical impact)
• Ignition of an easily ignited material
• Combustion of the material releases sufficient heat energy to ignite surrounding, harder-to-ignite materials
Increasing Pressure

**Increases**
- Mechanical stress
- Material flammability
- Compression ignition
- Combustion rates

**Decreases**
- Energy required for ignition
- Autoignition temperature
- Oxygen index

**Independent of pressure**
- Heat of combustion (heat release)
So How Do We Protect These Systems?
Relief Valve

Soft seat?

- Flow friction at crack pressure may ignite the seat material kindling a stem and body fire
- Seat cold flow may promote adiabatic compression ignition
Relief Valve

Metal-to-metal seat?

• Valve chatter may generate particles resulting in particle impact ignition of a downstream fitting

• Valve chatter may gall the stem, disc or seat destroying the protective oxide layer
Rupture Discs

All rupture discs produce particles when they burst even “non-fragmenting” discs.

• Rupture disc upstream of a relief valve can result in:
  – Adiabatic compression ignition of PRV softgoods
  – Particle impact ignition of PRV seat, plug, or disc

• Particle ignition of short radius elbows immediately downstream of the disc
Utilize Good Practices

• Design for ballistic flow
  – Long radius elbows instead of standard 90’s
  – “Y’s” instead of Tees
  – Minimum fittings and pipe in discharge line
• Reduce velocity ahead of targets
• Prevent system contamination
  – Insects are extremely flammable
  – Water will freeze
  – Consider a vent cover, such as Enviro-Guard rather than a vent tee with bug screen
Utilize Good Practices

- Treat the vent system with the same care as the process system
- Assemble components using “oxygen clean” techniques
- Thoroughly clean the system and sample the system
  - System must be designed for cleaning
## Maximize Best Materials

### High Oxygen Pressure and Low Propagation Rate

<table>
<thead>
<tr>
<th>Material</th>
<th>Initial Pressure psig</th>
<th>Average Propagation Rate in./s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monel 400</td>
<td>8000</td>
<td>NP</td>
</tr>
<tr>
<td>Copper 102</td>
<td>8000</td>
<td>NP</td>
</tr>
<tr>
<td>Nickel 200</td>
<td>8000</td>
<td>NP</td>
</tr>
<tr>
<td>Yellow brass</td>
<td>7000</td>
<td>NP</td>
</tr>
<tr>
<td>Tin bronze</td>
<td>7000</td>
<td>NP</td>
</tr>
<tr>
<td>Red brass</td>
<td>7000</td>
<td>NP</td>
</tr>
<tr>
<td>Inconel 600</td>
<td>2500</td>
<td>0.16</td>
</tr>
<tr>
<td>304 SS</td>
<td>2500</td>
<td>0.44</td>
</tr>
<tr>
<td>316 SS</td>
<td>1000</td>
<td>0.44</td>
</tr>
<tr>
<td>Ductile cast iron</td>
<td>500</td>
<td>0.14</td>
</tr>
<tr>
<td>Nitronic 60</td>
<td>500</td>
<td>0.33</td>
</tr>
<tr>
<td>Aluminum bronze</td>
<td>500</td>
<td>1.09</td>
</tr>
<tr>
<td>Aluminum 6061</td>
<td>250</td>
<td>1.80</td>
</tr>
</tbody>
</table>

ASTM G94-05, Table X1.1
# Maximize Best Materials

**Friction Ignition and Heat of Combustion**

<table>
<thead>
<tr>
<th>Material</th>
<th>Friction Ignition Test W/m² x 10⁻⁸</th>
<th>Heat of Combustions Cal/g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nickel 200</td>
<td>2.29</td>
<td>585</td>
</tr>
<tr>
<td>Copper 102</td>
<td></td>
<td>655</td>
</tr>
<tr>
<td>Tin bronze</td>
<td>2.15</td>
<td>690</td>
</tr>
<tr>
<td>Red brass</td>
<td></td>
<td>655</td>
</tr>
<tr>
<td>Inconel 600</td>
<td>2.00</td>
<td>1300</td>
</tr>
<tr>
<td>Monel 400</td>
<td>1.44</td>
<td>870</td>
</tr>
<tr>
<td>Yellow brass</td>
<td>0.95</td>
<td>825</td>
</tr>
<tr>
<td>Aluminum bronze</td>
<td></td>
<td>1400</td>
</tr>
<tr>
<td>304 SS</td>
<td>0.85</td>
<td>1900</td>
</tr>
<tr>
<td>316 SS</td>
<td>0.53</td>
<td>1900</td>
</tr>
<tr>
<td>Nitronic 60</td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td>Aluminum 6061</td>
<td>0.061</td>
<td>7524</td>
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<tr>
<td>Ti-6Al-4V</td>
<td>0.004</td>
<td>4710</td>
</tr>
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</table>

ASTM G94-05, Table X1.2, Table X1.5
**Maximize Best Materials**

Ignitability in Supersonic Particle Impact Test with 2000 µm Aluminum Particles, Oxygen Pressure 520 to 580 psia

<table>
<thead>
<tr>
<th>Material</th>
<th>Highest Temperature without Ignition of Target °F</th>
<th>Lowest Temperature with Ignition of Target °F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monel K500</td>
<td>700</td>
<td></td>
</tr>
<tr>
<td>Monel 400</td>
<td>650</td>
<td></td>
</tr>
<tr>
<td>Copper 102</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>Yellow brass</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>Inconel 600</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>Tin bronze</td>
<td>550</td>
<td></td>
</tr>
<tr>
<td>Aluminum bronze</td>
<td>500</td>
<td>600</td>
</tr>
<tr>
<td>Ductile cast iron</td>
<td>300</td>
<td>400</td>
</tr>
<tr>
<td>316 SS</td>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>Nitronic 60</td>
<td>0</td>
<td>250</td>
</tr>
<tr>
<td>304 SS</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Aluminum 6061</td>
<td>None</td>
<td>-50</td>
</tr>
</tbody>
</table>

ASTM G94-05, Table X2.9
# Maximize Best Materials

Autoignition Temperature and Heat of Combustion

<table>
<thead>
<tr>
<th>Material</th>
<th>Autoignition Temperature °F</th>
<th>Heat of Combustion Cal/g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teflon PFA</td>
<td>795</td>
<td>1250</td>
</tr>
<tr>
<td>Teflon A</td>
<td>813</td>
<td>1526</td>
</tr>
<tr>
<td>Rulon E (glass filled TFE)</td>
<td>801</td>
<td>1700</td>
</tr>
<tr>
<td>Kalrez</td>
<td>671</td>
<td>2090</td>
</tr>
<tr>
<td>PCTFE (Kel-F 81)</td>
<td>712</td>
<td>2500</td>
</tr>
<tr>
<td>Viton B</td>
<td>554</td>
<td>3089</td>
</tr>
<tr>
<td>PVDF (Kynar)</td>
<td>514</td>
<td>3277</td>
</tr>
<tr>
<td>Tefzel (ETFE)</td>
<td>469</td>
<td>3538</td>
</tr>
<tr>
<td>Viton A</td>
<td>514</td>
<td>3603</td>
</tr>
<tr>
<td>Vespel SP-21</td>
<td>649</td>
<td>6100</td>
</tr>
<tr>
<td>Zytel (Nylon 6/6)</td>
<td>498</td>
<td>7708</td>
</tr>
<tr>
<td>PEEK</td>
<td>581</td>
<td>6665</td>
</tr>
<tr>
<td>EPDM</td>
<td>318</td>
<td>11299</td>
</tr>
</tbody>
</table>

ASTM G63, Table X1.2, Table X1.5
# Maximize Best Materials

## Mechanical Impact Sensitivity

<table>
<thead>
<tr>
<th>Material</th>
<th>Impact Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rulon E (glass filled TFE)</td>
<td>0 / 20</td>
</tr>
<tr>
<td>PCTFE (Kel-F 81)</td>
<td>0 / 20</td>
</tr>
<tr>
<td>PVDF (Kynar)</td>
<td>79 / 100</td>
</tr>
<tr>
<td>Viton A</td>
<td>3 / 20</td>
</tr>
<tr>
<td>Zytel (Nylon 6/6)</td>
<td>21 / 60</td>
</tr>
</tbody>
</table>

ASTM G63, Table X1.4
# Maximize Best Materials

## Autoignition Temperature

<table>
<thead>
<tr>
<th>Material</th>
<th>Autoignition Temperature °F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brayco 667 (grease)</td>
<td>801</td>
</tr>
<tr>
<td>PTFE pipetape</td>
<td>801</td>
</tr>
<tr>
<td>Fluorolube GR362 (grease)</td>
<td>801</td>
</tr>
<tr>
<td>Fluorolube LG160 (grease)</td>
<td>720</td>
</tr>
<tr>
<td>Fomblin RT-15 (grease)</td>
<td>801</td>
</tr>
<tr>
<td>Halocarbon X90-15M</td>
<td>801</td>
</tr>
<tr>
<td>Krytox 240</td>
<td>801</td>
</tr>
<tr>
<td>Oxygen System Antiseize</td>
<td>424</td>
</tr>
<tr>
<td>Utility pipe joint compound</td>
<td>421</td>
</tr>
</tbody>
</table>

ASTM G63, Table 1.3
Summary

• Problem
  – Fire hazard risk is real in $O_2$ Relief systems
  – Fire consequences are often severe

• Solution
  – Use Risk Management Strategy
    • Minimize ignition hazards
    • Maximize best materials
    • Utilize good practices
Summary

• Design relief system for cleanability
• Design relief system for ballistic flow
• Specify the right metals, softgoods, and lubricants
• Specify the best assembly techniques
• Have materials tested if data is not available
• Conduct a full hazard analysis
Summary

Resources

• ASTM
  – Manual 36, Safe Use of Oxygen and Oxygen Systems
  – G 88 - system design
  – G 63 & G 94 - material selection and data
  – G 93 - oxygen system cleanliness
• CGA G04, Oxygen
• NFPA 53, Manual on Fire Hazards in Oxygen-Enriched Atmospheres
• Other options
  – Material testing, NASA White Sands Test Facility
  – Joel Stoltzfus, NASA White Sands Test Facility
Conclusions

• Safe oxygen use and relief is possible
• This is not an exact science
  – Many variables are involved
  – But applicable data and knowledge exist
  – And good principles have been established
• A conservative approach is essential
  
  Key element is judgment!