Spacecraft and Navy Materials

Flammability

Review of Some Concepts and Test Methods

David Hirsch
Agenda

- Concepts of spacecraft fire safety
- Spacecraft materials flammability test methods
- Evaluation of flight hardware flammability
- Review of flammability data in conditions of interest to the Navy
- Overview of some flammability test methods recommended for the Navy
Spacecraft Fire Safety

General strategy: prevent fires

- Materials control
- Minimizing potential ignition sources and materials that can propagate a fire
- Controlling the quantity and configuration of flammable materials to eliminate fire propagation paths
Spacecraft Fire Safety (Continued)

Risk management

- Accepted worst case
- Fire extinguishers

U.S. spacecraft fire history
Spacecraft Conditions
Maximum $O_2$ % and pressures for NASA spacecraft

- Space Shuttle Orbiter Cabin
  - maximum during normal operations: 25.9% $O_2$, 14.5 psia
  - during EVA preparation: 30% $O_2$, 10.2 psia

- Space Shuttle Orbiter Payload Bay: 20.9% $O_2$, 14.7 psia (Ground)

- Space Station Internal: 24.1% $O_2$, 14.5 psia

- Space Station Airlock: 30% $O_2$, 10.2 psia

- Space Station External: 20.9% $O_2$, 14.7 psia (Ground)
Spacecraft Conditions (Continued)

- Microgravity
- Forced convection
- Enclosed space
Flammability of Flight Hardware - Technical Requirements

- NASA-STD-6001
- NSTS 1700.7B - Safety Policy and Requirements for Payloads Using the Space Transportation System
- SSP 30233 - Space Station Requirements for Materials and Processes
Required materials tests are conducted per NASA STD 6001

- Test 1 - Upward flammability
- Test 2 - Heat and visible smoke release rates using a cone calorimeter
- Test 4 - Wire insulation flammability
- Test 18 - Arc-tracking
- Configurational flammability tests
NASA STD 6001 Test 1

- Upward flame propagation on vertical samples
- Quiescent environment. Worst environment conditions (% oxygen, pressure)
- Point ignition source provided by a chemical igniter
- Sample dimensions: 2.5 in. wide x 12 in. long x worst case thickness
Test 1 (Continued)
Test 1 (Continued)

Major measurements:
- burn length
- burn propagation time
- Ignition of K-10 paper
NASA STD 6001 Test 2
Heat and Visible Smoke Release Rates Using an Oxygen Consumption Calorimeter

- Test method based on the relationship between materials heat of combustion and the amount of oxygen required for combustion

- Test system similar with the system used by ASTM E 1354
Test 2 (Continued)

- 4 x 4 in. samples are exposed to a predetermined radiant energy (25, 50, or 75 kW/m²) under flowing oxygen/nitrogen mixtures.

- Sample is autoignited, or burning can be initiated by a spark ignition.
Test 2  (Continued)

- Exhaust blower
- Soot collection filter
- Controlled flow rate
- Gas samples taken here
- Soot sample tube
- Load cell
- Laser photometer including temperature
- Temperature and pressure measurements taken
- Exhaust hood
- Cone heater
- Spark igniter
- Specimen
- Vertical orientation

Temperature and pressure measurements taken using a laser photometer including temperature, controlled flow rate, and soot sample tube. Gas samples taken here and exhaust hood. Cone heater with spark igniter and specimen. Load cell and vertical orientation.
Test 2 (Continued)

Major measurements:
- oxygen concentration
- combustion gas temperature and flow rate
- sample mass loss rate
- time to sustained flaming
- smoke obscuration
Test 2 (Continued)

Data obtained:

- Average heat release rate
- Peak heat release rate
- Total heat released
- Effective heat of combustion
- Ignition time
- Smoke obscuration
- CO and CO$_2$ in combustion products
NASA STD 6001 Test 4

- Upward flame propagation on a powered sample installed at 15 degrees from vertical
- Quiescent environment. Worst environment conditions (% oxygen, pressure)
- Point ignition source provided by a chemical igniter
- Sample test section: 12 in. long
Test 4 (Continued)
Test 4 (Continued)

Major measurements:
- burn length
- burn propagation time
- Ignition of K-10 paper
How is NASA test data used for materials selection?

- Pass/fail criteria
- Material usage agreements

Some issues

- Simulation by ground tests of spacecraft conditions (correlation between ground test data and real life)
  - Quiescent environment vs. forced convection
  - Normal gravity vs. microgravity
Extinction boundary for a diffusion flame stabilized over a condensed fuel

Fr = 0
Fully convective

Fr \to \infty
Fully buoyant

Large Da
Quenching

Small Da
Blowoff

Oxygen concentration

Convection velocity

Steady flame
Experimental information on quiescent environments vs. forced convection flow effects on flammability

- **Ground tests:** free convection with gas linear velocity of 50 to 75 cm/s

- **Spacecraft:** forced convection with linear velocities of 10 to 15 cm/s
Experimental information on normal gravity vs. microgravity effects on flammability

- An upward flame propagation test performed under normal gravity would support flaming combustion under less severe oxygen concentration environments than those under which extinguishment would occur in a quiescent microgravity environment.

- Melting of thermoplastics could generate bubbles with increased bursting strength in microgravity, when burning gaseous and/or molten fuel could be ejected forcibly.
Flammability Tests on Flight Hardware

- A flammability configuration analysis is performed and/or flammability tests are conducted when components are flammable
- Example 1
- Example 2
Navy - Environments of interest

- ambient air - ships
- enclosed space - submarines
- possibility of oxygen depletion in a submarine fire. Note that sub-ambient oxygen concentrations may be worse environments than air for generation of toxic combustion products
- hyperbaric environments for diving; other diluents than nitrogen
Navy - additional flammability parameters of interest

- Spacecraft fire safety strategy focuses on prevention - by rigorous materials control. In microgravity environments, flammability is strongly dependent on oxygen availability; therefore, stopping free convection in a spacecraft is a strong deterrent to post-ignition flame development. Consequently, NASA’s interest in post-ignition fire properties is secondary to materials ignitibility.
Navy - additional flammability parameters of interest (continued)

- Due to its specific operating conditions, the Navy’s interest may well go beyond determining ignition characteristics.

- Post-ignition fire properties also could be of interest. Such properties include flame spread and burn rates; heat and smoke release rates; and toxicity of combustion products. Also, a developing fire could affect both ignition and post-ignition fire properties of surrounding materials through generation of radiant energy.
Flammability under hyperbaric conditions

- Oxygen partial pressure vs oxygen percentage
  
  Example:
  
  30.0% O₂, 10.2 psia (pO₂ = 3.06 psia)
  21.9% O₂, 14.7 psia (pO₂ = 3.08 psia)

- Effects of oxygen concentration and total pressures on ignition and flammability characteristics
Flame speed - total pressure relationship

The diagram illustrates the relationship between burning rate (cm/sec) and pressure (ATA) for various oxygen concentrations at different total pressures. The graph shows how the burning rate changes with pressure at different oxygen compositions, with oxygen concentrations ranging from 15.2% to 50.3%.
Flame speed - oxygen concentration relationship

![Graph showing the relationship between flame speed and oxygen concentration for different materials: PTFE, Vitron, Nylon 6/6, and PMMA. The graph plots flame speed (mm/min) against oxygen concentration (%).]
Autoignition temperature - oxygen concentration and pressure effects

![Graph showing the relationship between AIT (Autoignition Temperature) and pressure for different materials. The graph includes data points for Fluorel E-2160, Vespel SP-21, Nylon 6/6, and Neoprene.]
Limiting oxygen index - pressure effects

![Graph showing limiting oxygen index vs. absolute pressure for different materials.]

- PTFE
- Vitron
- Neoprene
- Nylon 6/6
- Glass-Filled Nylon 6/6
- PMMA

Oxygen Index (%) vs. Absolute Pressure (atm)
MIL-STD-2031

- Oxygen-temperature index
- Flame spread index per ASTM E 162
- Ignitibility, heat release, combustion gas generation per ASTM E 1354
- Smoke obscuration per ASTM E 662
- Burn-through fire test
- Quarter-scale fire test
- Large scale open and pressurizable fire tests
- N-gas Model smoke toxicity screening test
Oxygen Index

D 2863

- PTFE > 99.5
- PCTFE > 99.5
- Silicone 45.4
- Zytel 42 31.8
- Viton A 31.5
- Neoprene 23.9
- PE 17.5
- Delrin 17.2
## Oxygen Index

<table>
<thead>
<tr>
<th>Material</th>
<th>D 2863</th>
<th>Upward LOI</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTFE</td>
<td>&gt; 99.5</td>
<td>49.0</td>
</tr>
<tr>
<td>PCTFE</td>
<td>&gt; 99.5</td>
<td>54.3</td>
</tr>
<tr>
<td>Silicone</td>
<td>45.4</td>
<td>23.5</td>
</tr>
<tr>
<td>Zytel 42</td>
<td>31.8</td>
<td>23.0</td>
</tr>
<tr>
<td>Viton A</td>
<td>31.5</td>
<td>22.5</td>
</tr>
<tr>
<td>Neoprene</td>
<td>23.9</td>
<td>17.5</td>
</tr>
<tr>
<td>PE</td>
<td>17.5</td>
<td>17.5</td>
</tr>
<tr>
<td>Delrin</td>
<td>17.2</td>
<td>11.5</td>
</tr>
</tbody>
</table>

Hirsch et al.
Flame spread index per ASTM E 162

- Radiant heat energy source
- Downward burning on a sample inclined at 30 degrees from vertical
- Major measurements: Surface flame velocity and combustion gas temperature
- A flame spread index defined as a product of a flame spread factor and a heat evolution factor
Flame spread index per ASTM E 162

Some issues:

- Downward flame spread
- Thermocouple measurements
<table>
<thead>
<tr>
<th>Material</th>
<th>20 kW/m²</th>
<th>50 kW/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy</td>
<td>337</td>
<td>62</td>
</tr>
<tr>
<td>Epoxy/fiberglass</td>
<td>320</td>
<td>57</td>
</tr>
<tr>
<td>Nylon 6/6</td>
<td>700</td>
<td>74</td>
</tr>
<tr>
<td>PEEK</td>
<td>NI</td>
<td>142</td>
</tr>
<tr>
<td>Phenolic/fiberglass</td>
<td>NI</td>
<td>165</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>403</td>
<td>58</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>120</td>
<td>27</td>
</tr>
</tbody>
</table>

Scudamore et al
<table>
<thead>
<tr>
<th>Material</th>
<th>25 kW/m²</th>
<th>50 kW/m²</th>
<th>75 kW/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>polycarbonate</td>
<td>NI</td>
<td>99</td>
<td>44</td>
</tr>
<tr>
<td>polyethylene</td>
<td>141</td>
<td>70</td>
<td>35</td>
</tr>
<tr>
<td>PVC</td>
<td>485</td>
<td>421</td>
<td>69</td>
</tr>
<tr>
<td>Navy req (minimum)</td>
<td>300</td>
<td>150</td>
<td>90</td>
</tr>
</tbody>
</table>

- assumed piloted?

Holbrow et al
Comparison of ignitibility in various tests

<table>
<thead>
<tr>
<th>Material</th>
<th>UL94V 1mm thick</th>
<th>UL 94 V 2 mm thick</th>
<th>Min heat flux, kW/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTFE</td>
<td>V-0</td>
<td>V-0</td>
<td>33</td>
</tr>
<tr>
<td>PVC</td>
<td>V-1</td>
<td>V-2</td>
<td>8</td>
</tr>
<tr>
<td>PVC, FR</td>
<td>V-0</td>
<td>V-0</td>
<td>11</td>
</tr>
</tbody>
</table>

O’Neill et al.
# E 1354 results at 70 kW/m²

<table>
<thead>
<tr>
<th>Material</th>
<th>TTI</th>
<th>PRHR</th>
<th>ARHR</th>
<th>TTI/RHR</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTFE</td>
<td>252</td>
<td>161</td>
<td>53</td>
<td>1.56</td>
</tr>
<tr>
<td>PCARB</td>
<td>75</td>
<td>342</td>
<td>115</td>
<td>0.22</td>
</tr>
<tr>
<td>PE</td>
<td>47</td>
<td>2735</td>
<td>911</td>
<td>0.02</td>
</tr>
<tr>
<td>XLPE</td>
<td>35</td>
<td>268</td>
<td>194</td>
<td>0.13</td>
</tr>
</tbody>
</table>

*Navy req @ 75 kW/m²*
- minimum: 90
- maximum: 100

Babrauskas et al.
HRR vs. time for PTFE
HRR vs. time for PCARB

![Graph showing HRR vs. time for PCARB with different heat flux levels (20 kW/m², 40 kW/m², 70 kW/m²).]
HRR vs. time for PE
HRR vs. time for XLPE
Achieving non-flammability

- Using halogenated polymers
- Using polymers that upon decomposition leave more than 60% of their mass as char
- Incorporating flame retardant

Drawback:
- Toxicity and corrosivity of combustion products
MIL-STD 2031 - Combustion gas generation (per E 1354)

Maximum combustion gas produced at 25 kW/m²

- CO: 200 ppm
- CO₂: 4% by volume
- HCN: 30 ppm
- HCl: 100 ppm
Combustion gas generation (Continued)

Some issues:

- Generally a wider range of compounds are being sought - including HBr, HF, NO$_x$
- Fires in enclosed environments would deplete the oxygen and thus create conditions for generation of different combustion products, perhaps more toxic
- E 1354 does not simulate this situation
Mil-Std-2223
Test Methods for Insulated Electrical Wires

- Preparing activity: Navy
- Method 3006 - Wet arc-propagation resistance
- Method 3007 - Dry arc-propagation resistance
# Arc tracking test methods comparison

<table>
<thead>
<tr>
<th>Ranks/Qualifies</th>
<th>Mil-Std-2223 - 3006/3007</th>
<th>NASA STD 6001</th>
<th>ASTM D 3032</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-wire bundle</td>
<td>X</td>
<td>X</td>
<td>R</td>
</tr>
<tr>
<td>400 Hz, 3 phase, 120/208 V</td>
<td>X</td>
<td>X</td>
<td>X – allows alternates</td>
</tr>
</tbody>
</table>
### Arc tracking test methods comparison (continued)

<table>
<thead>
<tr>
<th>Arc initiation</th>
<th>Voltage proof test</th>
<th>Visual damage</th>
<th>CB’s tripped</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-damaged wires/RB</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>NASA STD 6001</td>
<td>X</td>
<td>-</td>
<td>X</td>
</tr>
<tr>
<td>Graphite powder</td>
<td>-</td>
<td>X</td>
<td>-</td>
</tr>
<tr>
<td>ASTM D 2223</td>
<td>X</td>
<td>-</td>
<td>X</td>
</tr>
<tr>
<td>Reciprocating blade (RB)</td>
<td>X</td>
<td>-</td>
<td>X</td>
</tr>
<tr>
<td>3006/3007</td>
<td>X</td>
<td>-</td>
<td>X</td>
</tr>
</tbody>
</table>
SS800-AG-MAN-010/P-9290

- System Certification Procedures and Criteria Manual for Deep Submergence Systems

- Cat 3 - materials and components for which definitive information and experience is not available
SS800-AG-MAN-010/P-9290
Category 3 Materials

- Validation of acceptability must be provided
- SS800-AG-MAN does not specify acceptance tests for new components or materials
- Regarding flammability testing:
  Manufacturer’s flammability data is reviewed; if data is inconclusive, testing is required to determine if upon exposure to a standard ignition source the material will self-extinguish and not transfer burning debris
SS800-AG-MAN-010/P-9290

Flammability issues

- **Materials:**
  - Acceptable if self-extinguish immediately upon removal from flame
  - All others require review and approval of proposed quantities and locations

- **Alternate procedure for assemblies:**
  - Evaluate flammability of individual components, if heat is produced when energized, location suitability. Submit for review and approval.
Oxygen systems

Similar systems design strategy as NASA’s

- Limit rapid pressurization, velocity, flow impingement, high pressure sections, control of particle generation
- Minimize possibility of leaks
- Follow ASTM Standard Guides for Oxygen Service:
  - G63 - Evaluating non-metals
  - G94 - Evaluating metals
  - G88 - Designing systems for oxygen service