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# Spacecraft and Navy Materials Flammability

## Review of Some Concepts and Test Methods

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# 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

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# 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**

# Spacecraft Materials Flammability Assessment for Habitable Flight Compartments

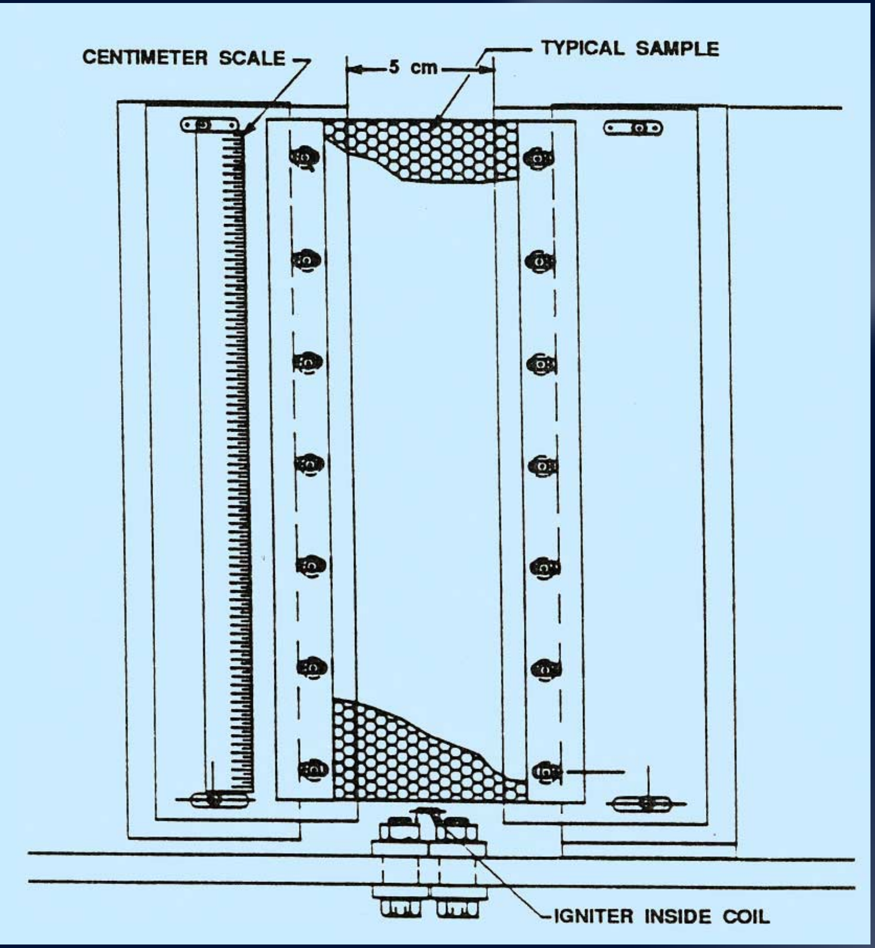
Required materials tests are conducted per NASA STD 6001

- 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

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# NASA STD 6001 Test 2

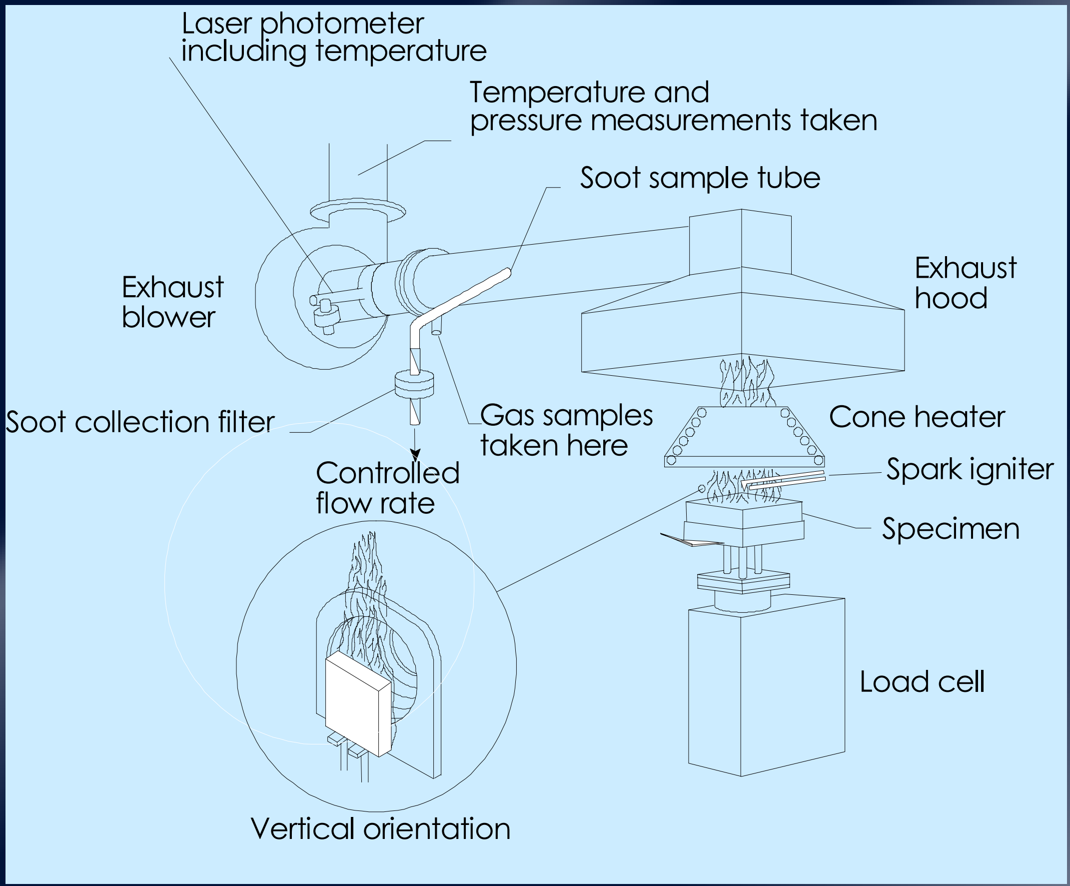
## Heat and Visible Smoke Release Rates Using an Oxygen Consumption Calorimeter

- 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 $kW/m^2$) under flowing oxygen/nitrogen mixtures
- Sample is autoignited, or burning can be initiated by a spark ignition

# Test 2 (Continued)



# 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

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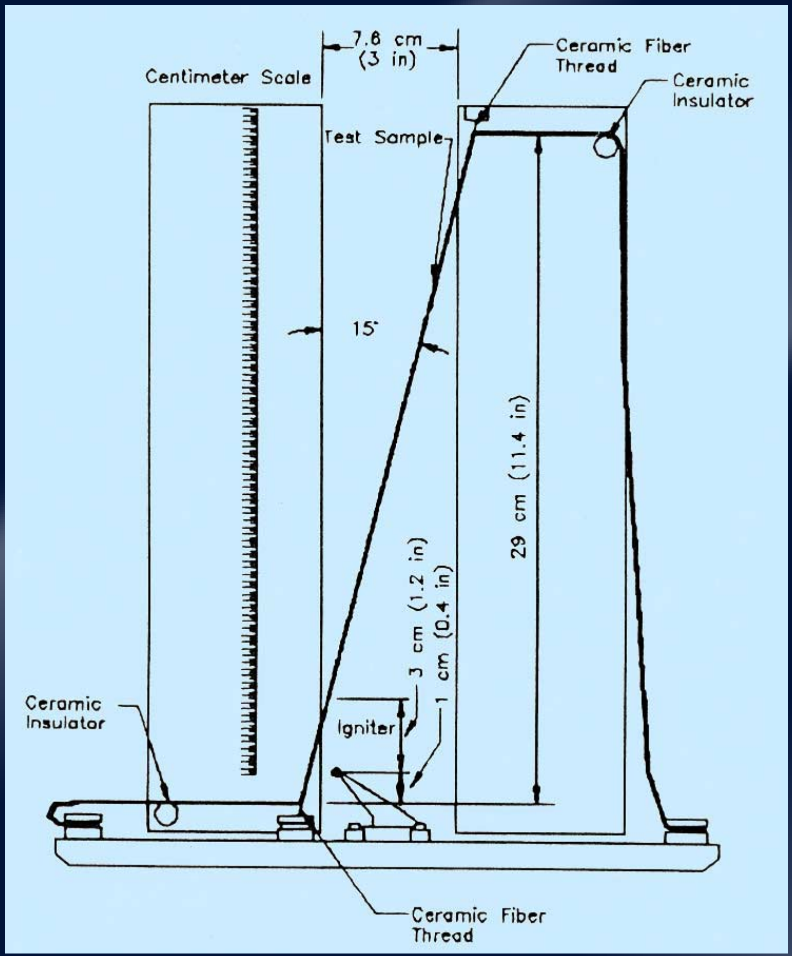
# Test 4 (Continued)



# Test 4 (Continued)

**Major measurements:**

- burn length
- burn propagation time
- Ignition of K-10 paper

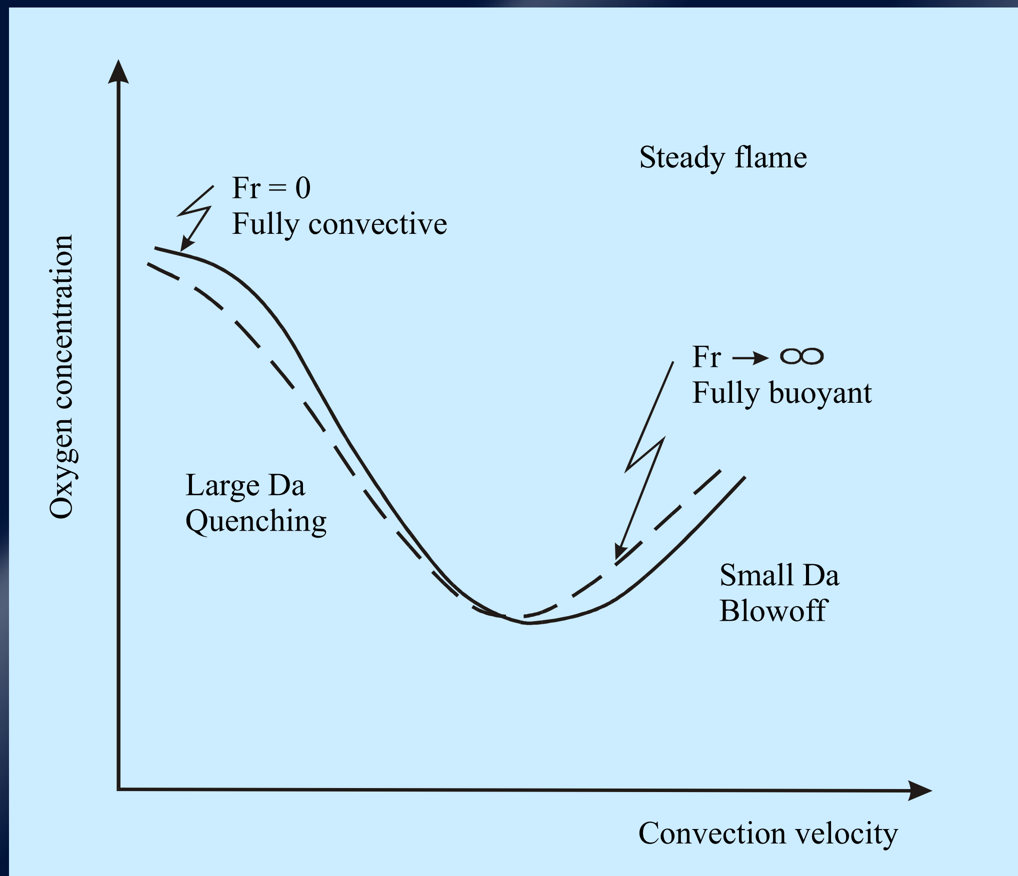
# How is NASA test data used for materials selection?

- 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



# 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

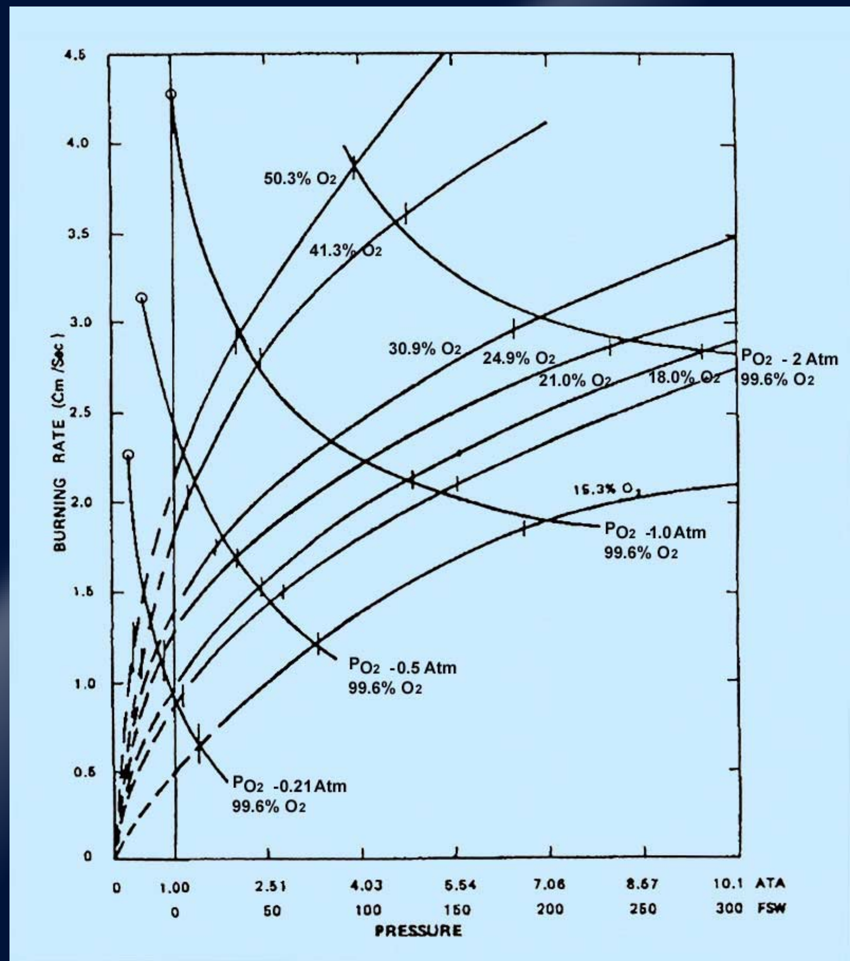
  Example:

  30.0% $O_2$, 10.2 psia ($pO_2$ = 3.06 psia)

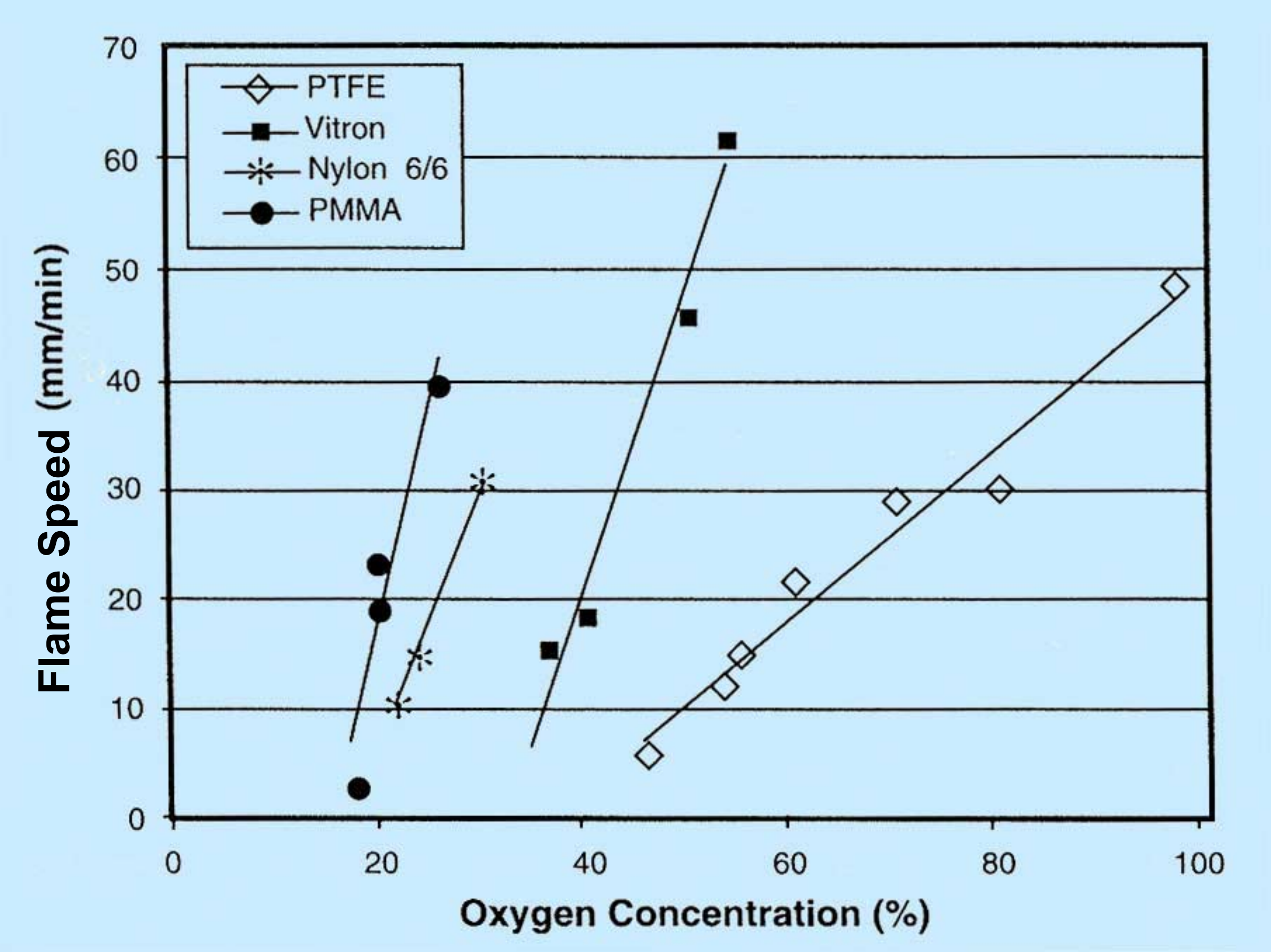
  21.9% $O_2$, 14.7 psia ($pO_2$ = 3.08 psia)

- Effects of oxygen concentration and total pressures on ignition and flammability characteristics

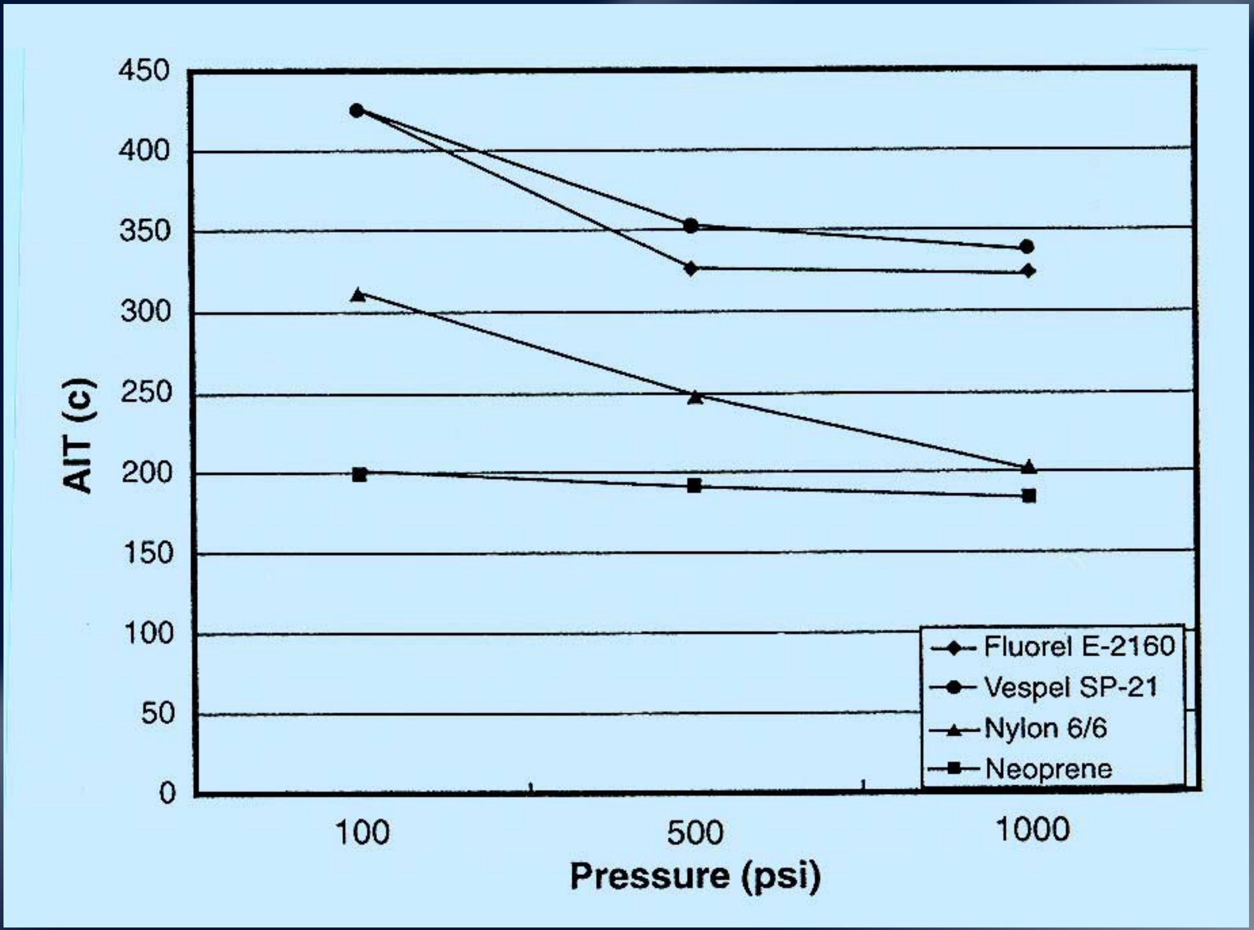
# Flame speed - total pressure relationship



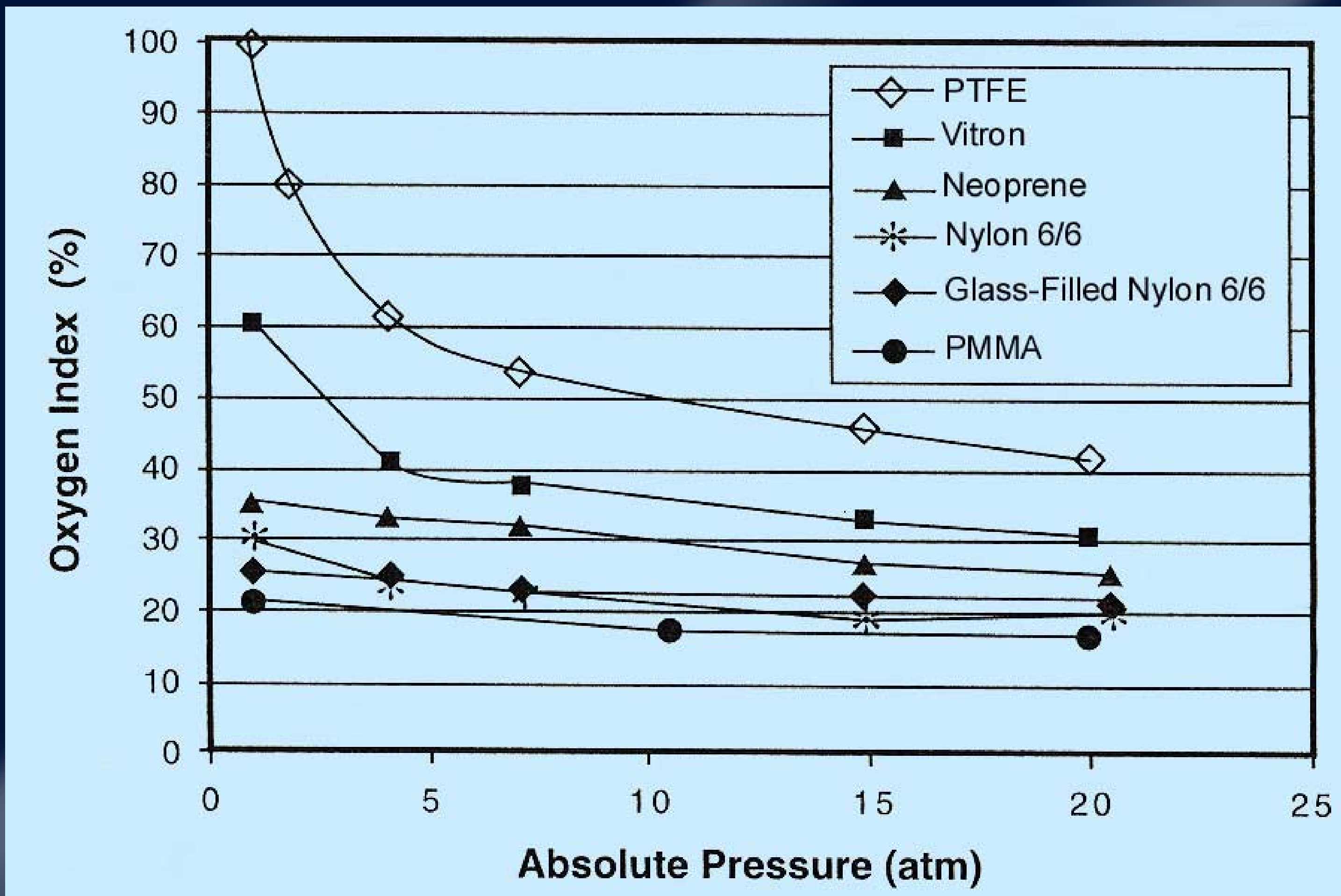
# Flame speed - oxygen concentration relationship



# Autoignition temperature - oxygen concentration and pressure effects



# Limiting oxygen index - pressure effects



# 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

| | D 2863 | Upward LOI |
|---|---|---|
| PTFE | > 99.5 | 49.0 |
| PCTFE | > 99.5 | 54.3 |
| Silicone | 45.4 | 23.5 |
| Zytel 42 | 31.8 | 23.0 |
| Viton A | 31.5 | 22.5 |
| Neoprene | 23.9 | 17.5 |
| PE | 17.5 | 17.5 |
| Delrin | 17.2 | 11.5 |

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

# E 1354 piloted ignition time (s)

| | 20 kW/m$^2$ | 50 kW/m$^2$ |
|---|---|---|
| Epoxy | 337 | 62 |
| Epoxy/fiberglass | 320 | 57 |
| Nylon 6/6 | 700 | 74 |
| PEEK | NI | 142 |
| Phenolic/fiberglass | NI | 165 |
| Polyethylene | 403 | 58 |
| Polypropylene | 120 | 27 |

Scudamore et al

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# E 1354 Autoignition time (s)

| | 25 kW/m$^2$ | 50 kW/m$^2$ | 75 kW/m$^2$ |
|---|---|---|---|
| **polycarbonate** | NI | 99 | 44 |
| **polyethylene** | 141 | 70 | 35 |
| PVC | 485 | 421 | 69 |
| ***Navy req (minimum)*** | ***300 - assumed*** | ***150 piloted?*** | ***90*** |

Holbrow et al

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# Comparison of ignitibility in various tests

| | **UL94V 1mm thick** | **UL 94 V 2 mm thick** | **Min heat flux, kW/m$^2$** |
|---|---|---|---|
| PTFE | V-0 | V-0 | 33 |
| PVC | V-1 | V-2 | 8 |
| PVC, FR | V-0 | V-0 | 11 |

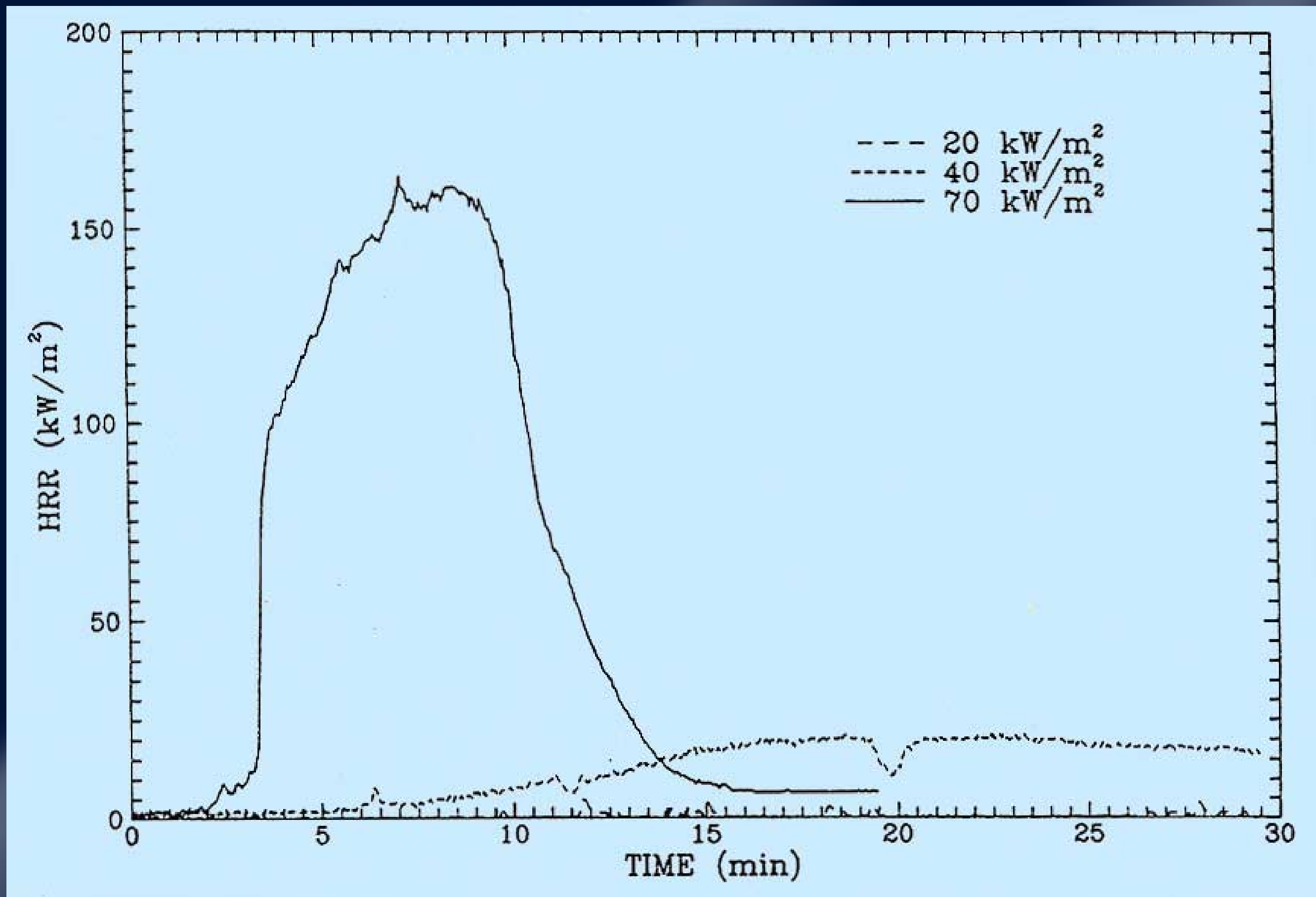
O'Neill et al.

# E 1354 results at 70 kW/m$^2$

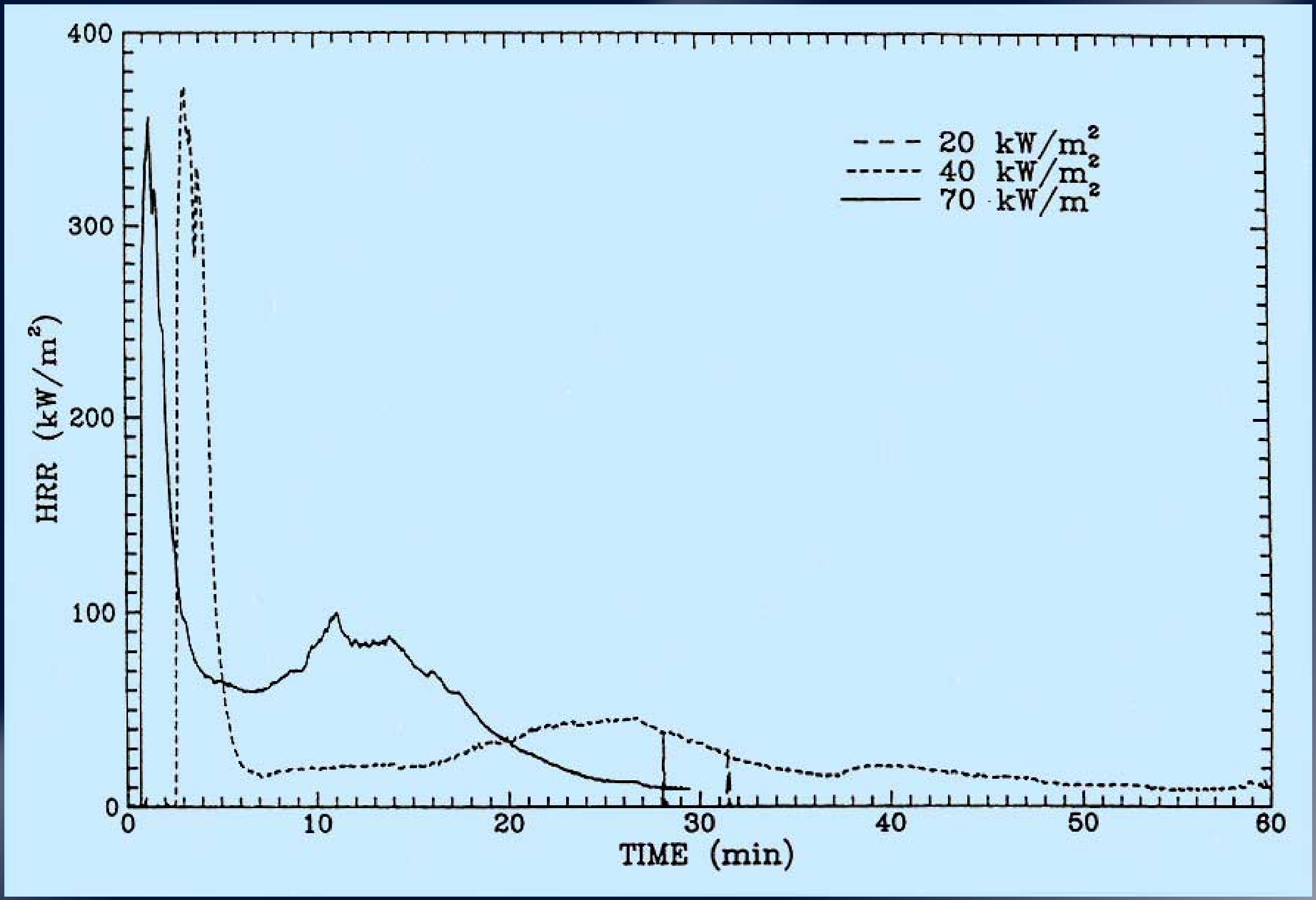
| | TTI | PRHR | ARHR | TTI/RHR |
|---|---|---|---|---|
| **PTFE** | 252 | 161 | 53 | 1.56 |
| **PCARB** | 75 | 342 | 115 | 0.22 |
| **PE** | 47 | 2735 | 911 | 0.02 |
| **XLPE** | 35 | 268 | 194 | 0.13 |
| ***Navy req @ 75 kW/m$^2$*** | ***90 minimum*** | ***100 maximum*** | ***100 maximum*** | ***-*** |

Babrauskas et al.

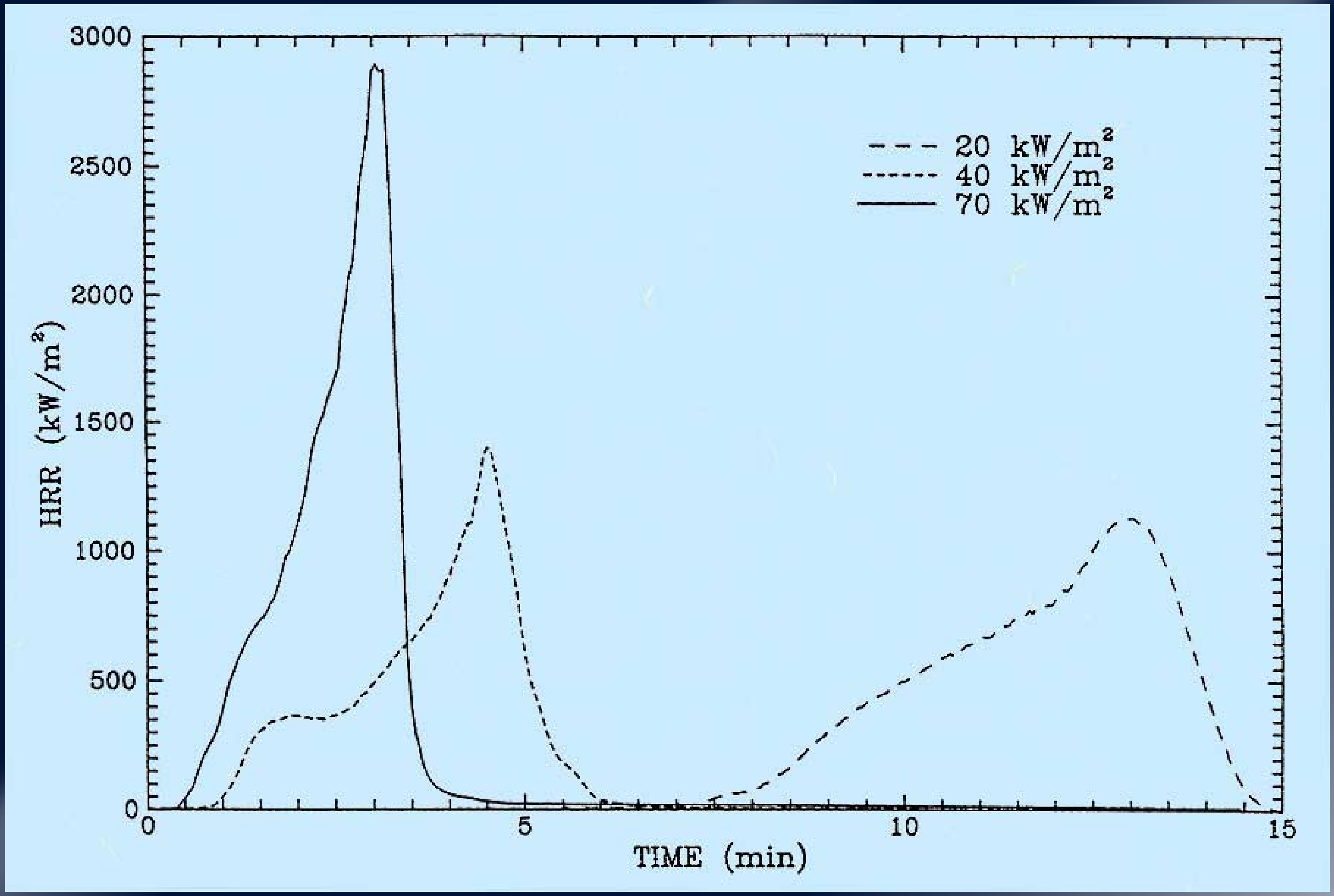
# HRR vs. time for PTFE



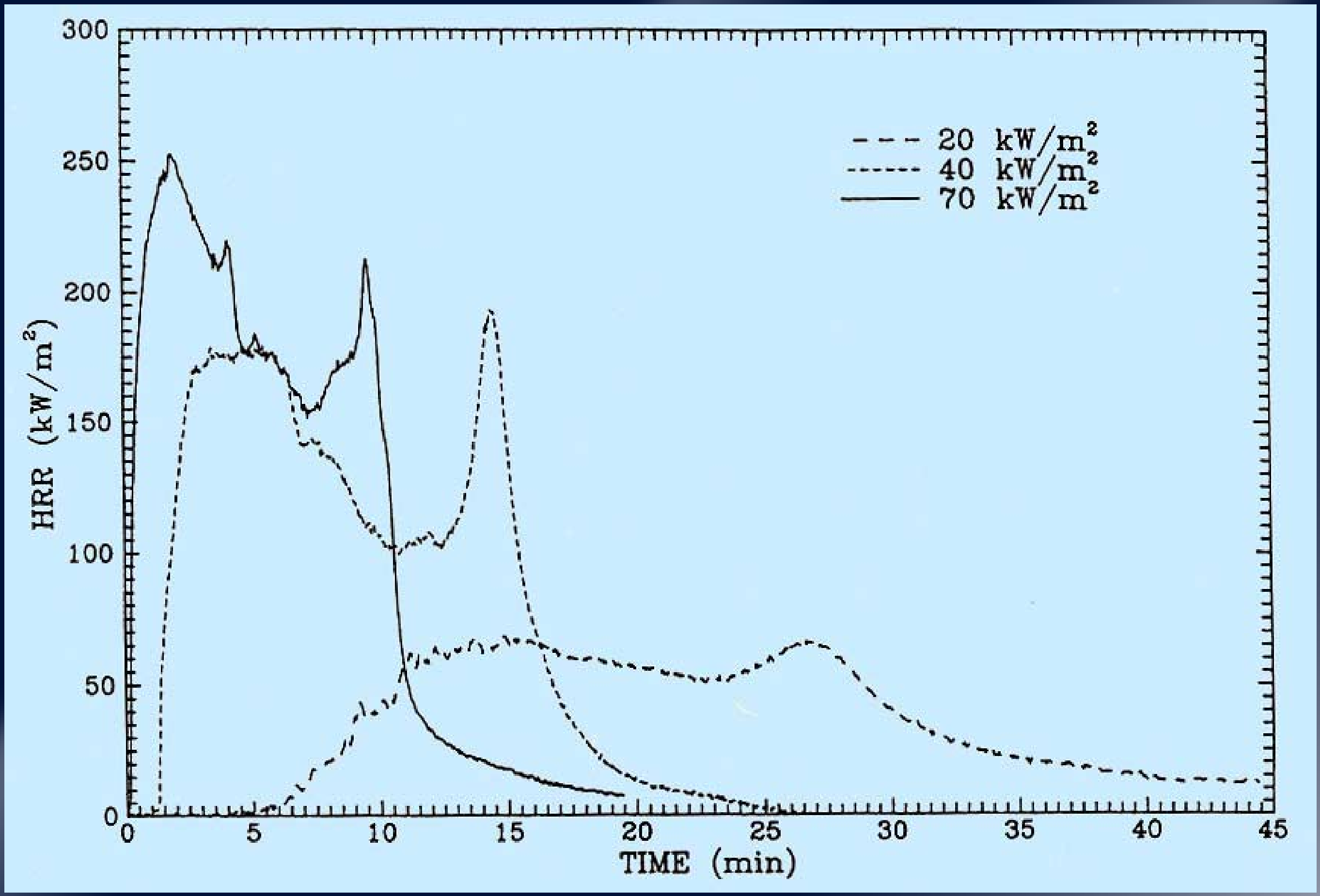
# HRR vs. time for PCARB



# HRR vs. time for PE



# HRR vs. time for XLPE



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# 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/m$^2$ |
|---|---|
| CO | 200 ppm |
| $CO_2$ | 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

| | Mil-Std-2223 - 3006/3007 | NASA STD 6001 | ASTM D 3032 |
|---|---|---|---|
| **Ranks/ Qualifies** | Q | Q | R |
| **7-wire bundle** | X | X | X |
| **400 Hz, 3 phase, 120/208 V** | X | X | X – allows alternates |

# Arc tracking test methods comparison (continued)

| | 3006/3007 | NASA STD 6001 | ASTM D 2223 |
|---|---|---|---|
| **Arc initiation** | Pre-damaged wires/RB | Graphite powder | Reciproca-ting blade (RB) |
| **Voltage proof test** | X | - | X |
| **Visual damage** | X | X | X |
| **CB's tripped** | X | - | X |

# 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.

# SS800-AG-MAN-010/P-9290 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