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UNMANNED VEHICLE MATERIAL FLAMMABILITY TEST

DAVID L. URBAN & GARY A. RUFF: NASA GLENN RESEARCH CENTER, USA
OLIVIER MINSTER & BALAZS TOTH: ESA ESTEC, NOORDWIJK, NETHERLANDS
A. CARLOS FERNANDEZ-PELLO: UC BERKELEY, BERKELEY, CALIFORNIA, USA
JAMES S. T'IEN: CASE WESTERN RESERVE UNIVERSITY, CLEVELAND, OHIO, USA
JOSE L. TORERO & ADAM J. COWLARD: UNIVERSITY OF EDINBURGH, EDINBURGH, UK
GUILLAUME LEGROS: UNIVERSITÉ PIERRE ET MARIE CURIE, PARIS, FRANCE
CHRISTIAN EIGENBROD: UNIVERSITY OF BREMEN (ZARM), BREMEN, GERMANY
NICKOLAY SMIRNOV: MOSCOW LOMONOSOV STATE UNIVERSITY, MOSCOW, RUSSIA
OSAMU FUJITA: HOKKAIDO UNIVERSITY, SAPPORO, JAPAN
SEBASTIEN ROUVREAU: BELISAMA R&D, TOULOUSE, FRANCE
GRUNDE JOMAAS: TECHNICAL UNIVERSITY OF DENMARK, KGS. LYNGBY, DENMARK
Spacecraft Fire Safety Demonstration

• Most U.S. agencies responsible for inhabited structures and transportation systems conduct full-scale fire tests to address gaps in fire safety knowledge and prove equipment and protocols.
• NASA has been unable to conduct such tests owing to risk to the crew.
• Unmanned vehicles provide a new opportunity.
• Demonstration of this operational concept could allow future experiments to investigate additional fire safety technologies and protocols or in unrelated areas.

Experiment Objective:
Determine the fate of a large-scale microgravity fire
1. Spread rate, mass consumption, and heat release
   • Is there a limiting size in microgravity?
2. Confirm that low-g flammability limits are less than those in normal gravity
   • Are drop tower results correct?
Knowledge Gaps

- Low- and partial-g flammability limits for spacecraft materials
- Hybrid gas and particulate sensors for fire detectors and post-fire monitoring
- Realistic fire challenges

- Common smoke detectors, fire extinguisher, post-fire response and monitoring equipment
  - Smoke-eater (Enabling)
  - Combustion Product Monitor
- Material flammability (margin of safety) at high %O₂
  - Improved detection and suppression to reduce risk (Enhancing)

- Common portable fire extinguisher for exploration
- Common Smoke Eater technology
- Demonstrating technologies in SFS Demo

Scalable!
Experiment Justification

- How different are low-g material flammability limits from those measured in normal gravity?
  - Low-gravity oxygen flammability limits are different in low-gravity than in normal gravity
  - Normal gravity flames induce a natural convective flow that transports oxygen to the flame but also removes heat
  - Forced convection in low-g transports oxygen to the flame but rate of heat removal is reduced
    - The normal-gravity (and partial-gravity) oxygen concentration flammability limit is not necessarily the minimum

- What is the fate of a large-scale fire in low-gravity?
  - Extrapolation of observed low-g flame behavior to a full-scale spacecraft fire scenario is tenuous
  - Experience with “significant” fires is very limited
    - Enhance risk assessments and modeling of fire events
How rapidly can a fire spread in low-g?

This question lies at the heart of the development of a fire safety strategy
- Terrestrial or spacecraft applications

Rate of fire growth impacts:
- Time to detect
  - How fast do you need to detect it?
- Size of fire
  - How long will it remain manageable?
  - Amount of fire suppression agent required
- Heat release rate, fire spread to surrounding materials
  - Collateral damage
- Emission of combustion products
  - Post-fire cleanup strategy and consumables

Large-scale flame spread sample
- 0.5 m wide x 1.0 m long

NIST Full Scale Fire test
FAA full scale aircraft test
Side view of a low-g flame on a thin paper sample in a concurrent convective flow
Implications of Fire Growth Rate

- Almost no information exists on large-scale fire growth in microgravity
- CO₂ concentration approximately scales with mass of material consumed
- Safety-critical parameters such as temperature and pressure scale with mass consumed and rate of mass consumption
- Growth rate information is needed to make informed decisions on safety equipment and crew response
  - Pressure relief valve sizing
  - Extinguisher size
  - Consumables for cabin cleanup
  - Crew response times (fight-or-flee decisions)
- Data will validate modeling of spacecraft fire response scenarios
Material Flammability Testing

- NASA-STD-6001 describes the test methods used to qualify materials for use in space vehicles.
- The tests cover flammability, odor, off-gassing, and compatibility.
- The primary test to assess material flammability is Test 1: Upward Flame Propagation

- Materials “pass” this test if the flame self-extinguishes before it propagates 15 cm
- Maximum oxygen concentration (MOC) is defined as the highest $O_2$ fraction at which material passes Test 1
- Flammability limits determined by this test are strongly influenced by natural convection
- Samples are 5 cm wide $\times$ 33 cm long and rigidly held in a frame

- Test 1 Apparatus

- Flammability samples
Low- and Partial-g Flammability Limits

- Tests were conducted at WSTF (normal-g) and GRC (low- and partial-g) to quantify changes in the flammability limit for Nomex, Mylar, and Ultem at low (with convective flow), Martian, and Lunar gravity levels.

- Data on right shows Oxygen Margin of Safety (negative means material burns at lower O2 compared to normal gravity!)

\[(\text{OMOS} = \text{MOC})_{0-g} - \text{MOC})_{1-g}\]

Centrifuge drop rig being prepared for a drop in the Zero Gravity Facility

- Flammability limit samples in the Spacecraft Fire Safety Demonstration Experiment will evaluate NASA-STD-6001 Test 1 in low-g and validate drop tower results.
Experiment Concept

- Project is developing an experimental concept for the Cygnus vehicle
- **Current objective is to produce a “simple” modular test facility that could be replicated and fly on multiple flights**
  - Achieve additional spacecraft fire safety demonstration objectives while achieving a lower cost per flight
- **Multiple, single-objective experiments on three flights**
  1. Single, large sample – large-scale flame spread
  2. Flammability limit samples – verify oxygen flammability limits in low gravity
  3. Repeat 1. or 2. at different conditions/post-fire clean-up

*Experiment flow duct concept*
*Interior of flow duct is 20” x 20” x 46”*
Mission Concept

Load experiment into Cygnus PCM

Cygnus mounted in the shroud of the Antares vehicle

Antares (Taures 2) V launch
Mission Concept

Cygnus approaching ISS

Unpack cargo, reload with trash

Proposed location of the SFS Demo experiment (back of vehicle)

Check-out SFS Demo experiment
SFS Demo Experiment Configuration

- Experiment remains on AFT wall but rotated to lie between the rails
- Sample spacing requirements met
- Length of flow chamber reduced from 48” to 44”
- Camera enclosures facing M-01/M-02 bags on AFT wall
Mission Concept

CAD model of SFS Demo in Cygnus

Side view of a low-g flame on a thin paper sample in a convective flow

NASA Ops Engr.

Cygnus Ops Engr.

Ground Stations

Data Receiving and Analysis

CRC Operations

S-Band Antenna

X-Band Antenna

Cygnus Comm

VOICE
Spacecraft Fire Safety Demo Mission Concepts

Details of experiment flow duct (draft)

Outer dimensions of experiment hardware
(Interior of flow chamber is 20” x 20” x 48”)

Block configuration of Cygnus experiment concept
Safety Considerations - Overpressure testing

Vacuum Faculty (VF)-13)
149.9 cm ID, 360 cm high, 6.35 m$^3$ volume
Safety Considerations - Overpressure testing

Pressure trace for Single 12.5- by 100-cm sample ignited at the top. The fuel is 90 grade cotton cheese-cloth with a 4.92 mg/cm² density.

SIBAL Cloth, upward 1-g
Calculations are initialized with a steady state flow generated by the fans at constant temperature following a classic strategy:

- Flow initialization
- Full multigrid initialization
- Few thousand iterations with first order solver
- Few thousand iterations with second order solver

Flow modelling main parameters:

- Energy equation turned on
- Turbulence model: Ke-RNG
- Air as ideal gas for density calculation
- Sutherland model for viscosity
- Initial temperature: 300k
- Initial pressure: 1013 hPa
- All walls are adiabatic
Calculation with heat release: ATV configuration

1- ATV configuration after 1 minute of heat release
   - Pathlines
   - Velocity field

Pathlines Colored by Velocity Magnitude (m/s) (Time=6.0000e+01)
ANSYS FLUENT 14.0 (3d, dp, pbns, rngke, transient)
Calculation with heat release: ATV configuration

1- ATV configuration after 1 minute of heat release
   - Temperature field
Conclusions

- Microgravity fire behaviour remains poorly understood and a significant risk for spaceflight.

- An experiment is underdevelopment that will provide the first real opportunity to examine this issue focusing on two objectives:
  - Flame Spread
  - Material Flammability

- This experiment has been shown to be feasible on both ESA’s ATV and Orbital Science’s Cygnus vehicles with the Cygnus as the current base-line carrier.

- An international topical team has been formed to develop concepts for that experiment and support its implementation:
  - Pressure Rise prediction
  - Sample Material Selection

- This experiment would be a landmark for spacecraft fire safety with the data and subsequent analysis providing much needed verification of spacecraft fire safety protocols for the crews of future exploration vehicles and habitats.