

#### Fire Safety in Space

Beyond Flammability Testing of Small Samples

Jomaas, Grunde

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# Fire Safety in Space –

# **Beyond Flammability Testing of Small Samples**



**GRUNDE JOMAAS** ASSOCIATE PROFESSOR DTU CIVIL ENGINEERING



# Goals for ISS and Space Design

- Safety for launch, personnel, hardware, uninvolved public
- Identify, control and document hazards
- Enable informed programmatic decisions
- Handle situations and continue successfully
- Redundancy
  - CO<sub>2</sub> removal system
  - Atmosphere Control System(ACS)
  - Oxygen supply system
- Robust, yet versatile
- Historical approach falls short (limited data)

# It is only going to get more challenging!



"We have not even begun to comprehend the complexities of fire safety in commercial space travel"

> NASA Decadal Review, National Academy of Sciences, 2010

# Progress related challenges

- Governmental Programs
  - SOYUZ launch of crew
  - Exploration
    - Beyond LEO (Low Earth Orbit), 2013-2021
    - Into the Solar System, 2021-2027
    - Exploring Other Worlds, 2027-2033
    - Planetary Exploration, 2033-
- Commercial Programs
  - Space X Dragon(w/ return)
  - Orbital Cygnus (COTS program)
  - Virgin Galactic (400+ have signed up)
    - Numerous other private enterprises
- Safety design becomes disconnected from the operator
  - Relies on fire safety test procedures from NASA
    - Spacecraft fire safety emphasizes fire prevention, which is achieved primarily through the use of fire resistant materials.
    - Materials selection for spacecraft is based on conventional flammability acceptance tests, along with prescribed quantity limitations and configuration control for items that are non-pass or questionable.



# NASA-STD-6001

- 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 (based on ASTM test): Upward Flame Propagation



- Materials "pass" this test if the flame selfextinguishes before it propagates 15 cm
- Maximum oxygen concentration (MOC) is defined as the highest O<sub>2</sub> at which material passes Test 1
- Flammability limits determined by this test are <u>strongly influenced by natural</u> <u>convection</u>
- Drop tower data shows that flammability limits are lower in low- and partial-gravity!
- Do NASA's flammability standards result in higher flammability limits than actually found in low-gravity?

## **Material Flammability**

- Mostly based on a "Worst Case Scenario" Test
- NASA Test 1



## Challenges





- Fires in micro-gravity will burn with a very different flow field:
  - Affects heat transfer
  - Affects mass transfer
  - Affects combustion
     chemistry





A. Kumar, H.Y. Shih, J.S. T'ien, Combustion and Flame, 2003

## Differences



# Understanding Flammability – Co-current flame spread





# **Relevant Parameters**



# The Emmons Solution (I)



Emmons H., The Film Combustion of Liquid Fuel, *Zeitschrift für Angewandte Mathematik und Mechanik*, Vol. 36, pp. 60, 1956.

# The Emmons Solution (II)



Emmons H., The Film Combustion of Liquid Fuel, *Zeitschrift für Angewandte Mathematik und Mechanik*, Vol. 36, pp. 60, 1956.

# The Emmons Solution (III)



Emmons H., The Film Combustion of Liquid Fuel, *Zeitschrift für Angewandte Mathematik und Mechanik*, Vol. 36, pp. 60, 1956.



difficult to evaluate

# Losses

$$Q = \frac{\left(\dot{q}_{L,C}'' + \dot{q}_{L,sr}'' - \dot{q}_{fr}''\right)}{\dot{m}_{f}''}$$

- Q decreases with the free stream velocity
- Q increases with "x"

$$\dot{m}_{f}'' = (\rho_{\infty}U_{\infty}) \frac{(\eta f' - f)}{2(\text{Re}.(x/L))^{1/2}}$$

# SPACECRAFT FIRE SAFETY DEMONSTRATION

# **Spacecraft Fire Safety Demonstration**

## Project Objective:

- Advance spacecraft fire safety technologies identified as gaps by the Constellation Program and in the Exploration Technology Roadmaps
- Demonstrate performance of these technologies in a large-scale, low-gravity spacecraft fire safety test aboard an unmanned re-entry vehicle
  - Demonstration of this operational concept could allow future experiments to investigate additional fire safety technologies and protocols

### 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- and partial-g flammability limits are less than those in normal gravity
  - Are drop tower results correct?

Most U.S. agencies responsible for large transportation systems conduct full-scale fire tests to address gaps in fire safety knowledge and prove equipment and protocols.



FAA full scale aircraft test



Naval Research Laboratory Ex-USS Shadwell



ESA's ATV approaching the ISS



Controlled burns of structures



Orbital Science's Cygnus approaching ISS

# Saffire

## Validation at realistic time and length scales with materials relevant to spacecraft

- Flammability analysis
- Forecasting by data assimilation

# International Team:

- Coordinator: Grunde Jomaas: Technical University of Denmark, Kgs. Lyngby, Denmark
- Nickolay Smirnov: Moscow Lomonosov State University, Moscow, Russia
- David L. Urban and Gary A Ruff: NASA Glenn Research Center, Cleveland, OH, USA
- A. Carlos Fernandez-Pello: UC Berkeley, Berkeley, CA, USA
- James S. T'ien: Case Western Reserve University, Cleveland, OH, USA
- José L. Torero University of Queensland, Brisbane, Australia
- Adam Cowlard: University of Edinburgh, Edinburgh, UK
- Sebastien Rouvreau: Belisama R&D, Toulouse, France
- Olivier Minster and Balazs Toth: ESA ESTEC, Noordwijk, Netherlands
- Guillaume Legros: Université Pierre et Marie Curie, Paris, France
- Christian Eigenbrod: University of Bremen (ZARM), Bremen, Germany
- Osamu Fujita: Hokkaido University, Sapporo, Japan







# **Spacecraft Fire Safety Demo Experiment Concept**



Details of experiment flow duct approximate size: 20" x 20" x 44"

Design choices driving simplified concept

- "Simple" modular test facility that can be replicated and fly on multiple Cygnus flights
- Only the sample card and test conditions are different in the three flights
- Multiple, single-objective experiments that address spacecraft fire safety gaps
  - 1. Single, large sample → large-scale flame spread (flame spread samples)
  - Six to twelve flammability limit samples → evaluate NASA-STD-6001 Test 1 and verify oxygen flammability limits in low gravity
  - 3. Repeat 1. or 2. at different conditions
- No safety-critical software; heritage based
- No crew interaction; fully assembled experiment
- Unpowered while attached to ISS
- Commanding originates from Orbital Sciences

## Spacecraft Fire Safety Demonstration Experiment Design



# Saffire Flight Unit Structure



• Dimensions: 35.3" x 21.0" x 52.5"

# Saffire Avionics Plate



# Assembly and Integration Status Avionics Panel Assembly

- Assembly and functional testing of Saffire-I, II, and III avionics panels completed in July 2014
- Tests of the low and high speed serial Cygnus interface showed compliance with our Saffire-Cygnus serial communications interface requirements.



Signal Conditioning Card



DAQ Cube

Avionics panel is 1.3 m long by 0.5 m wide

## Flight tests

### 1. Large Flame Spread sample

• Orbital-5: July 24, 2015

## 2. Material Flammability samples

• Orbital-6: January 4, 2016

## 3. Large Flame Spread Sample

• Orbital-7: June 19, 2016



# Assembly and Integration Status Flow Duct Assembly



### Flow duct instrumentation

- Radiometers
- $O_2$  sensor
- CO<sub>2</sub> sensor
- Pressure Transducer
- Anemometers
- Thermocouples

## **Saffire-2 Sample Details**

1 2 3	Sample #	Material	Sample Thickness	Air Flow (cm/s)	Igniter Position
4 5   6   7   8   9   1	Saffire-2-S1	Silicone (Flammability limit	0.25 mm (0.010")	20	Bottom
	Saffire-2-S2	1) Silicone (Flammability limit 2)	0.61 mm (0.024")	20	Bottom
	Saffire-2-S3	Silicone (Flammability limit 3)	1.02 mm (0.040")	20	Bottom
	Saffire-2-S4	Silicone (Downward burn 1)	0.36 mm (0.014")	20	Тор
	Saffire-2-S5*	SIBAL fabric (SIBAL 1)	0.33 mm (0.013")	20	Bottom
	Saffire-2-S6*	SIBAL fabric (SIBAL 2)	0.33 mm (0.013")	30	Bottom
	Saffire-2-S7*	PMMA to Nomex (Transition 1)	0.33 mm (0.013")	20	Bottom
	Saffire-2-S8**	Structured PMMA (Thick 1)	10 mm with tapered edge for ignition	20	Bottom
PMMA Silicone Nomex	Saffire-2-S9	Flat PMMA (Thick 2)	10 mm with tapered edge for ignition	30	Bottom
	* Samples S5, S6, and S7 get two thermocouples each; see pp. 2-3				

\*\* See detailed drawing on p. 4

# Science Status Saffire-II Sample Card

• Populated and wired sample card for Saffire-II



- Igniter wire "loops" on a silicone sample
  - Space upstream of sample allows edge ignition



## Saffire-2 Sample 5 and Sample 6 Details



## Saffire-2 Sample S7 (Transition: PMMA to Nomex) Details



# Science Status Modeling

- Xiaoyang Zhao and Prof. James T'ien (Case Western Reserve University) are expanding the capability of an existing flame spread model to simulate Saffire test conditions.
- "A Three-dimensional Transient Model for Flame Growth and Extinction in Concurrent Flows" at the 6<sup>th</sup> CFD Fire Modeling Workshop on May 15-16, 2014.
  - Model is for flame growth on samples similar in length and same material as Saffire-I and –III
  - Data from Saffire-I, -II, and –III experiments will be compared to extended versions of these models.







Temperature along center plan (colors) vs. time (top to bottom) for a buoyant flow condition. (In low-g, Saffire conditions will be in forced flow.)

## Saffire Development Schedule













# Astronaut View Looking Inside a Loaded Pressurized Cargo Module (PCM)

Proposed location of SFS Demo Experiment

• Experiment would use standard straps and replace cargo bags.



# **Experiment Configuration**

- Experiment replaces an M-01 and M-02 bag
- Fully assembled and installed into the PCM at Wallops Flight Facility (WFF)
  - Power and communication cables
- System check-out when attached to Service Module at WFF
- No crew interaction with the experiment
  - Experiment does not need to be moved during unloading or loading



- 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**



Load experiment into Cygnus PCM





Cygnus mounted in the shroud of the Antares vehicle

Antares Launch

# **Mission Concept**



# **Mission Concept**



## **Operations Concept**















Cygnus in Free Flight Outside ISS Safety Corridor

Saffire powered ON. Autonomous Experiment Sequence

Initiated

Cygnus Departs ISS

Saffire Unpowered



Cygnus Berthed to ISS

Saffire Unpowered No crew interaction required. PIA guidance on "trash" keep out zones around Saffire.



Santiago, Fucino, Chile Italy

Italy

WGS

Cygnus remains in orbit up to 8 days to downlink Saffire data.



ISS Rendevous, Prox Ops, and SSRMS Capture

Saffire Unpowered



Cygnus Destructively Re-enters Atmosphere With Saffire

## Saffire Overview

## Needs:

- Low-g flammability limits for spacecraft materials
- Definition of realistic fires for exploration vehicles
  - Fate of a large-scale spacecraft fire

## **Objectives:**

- Saffire-I: Assess flame spread of largescale microgravity fire (spread rate, mass consumption, heat release)
- Saffire-II: Verify oxygen flammability limits in low gravity
- Saffire-III: Same as Saffire-I at a different flow condition
- Data obtained from the experiment will be used to validate modeling of spacecraft fire response scenarios
- Evaluate NASA's normal-gravity material flammability screening test for low-gravity conditions.



Saffire module consists of a flow duct containing the sample card and an avionics bay. All power, computer, and data acquisition modules are contained in the bay. Dimensions are approximately 53- by 90- by 133-cm

## Future Flight – Wire array concept?



Typical arrangement of wire spreading test. Air flow is given from right to left.



## **Cygnus Vehicle Capability**

Airflow for Mid-Deck Lockers is part of the cabin (fire detection and suppression) airflow system





- Area smoke detector in ٠ Cygnus
  - Appears similar to the ISS detector

# Summary of Spacecraft Fire Safety Needs

## Material Flammability

- Low- and partial-g flammability limits for spacecraft materials
- Material flammability at high %O<sub>2</sub> and reduced pressure
- Realistic fire challenges

## Fire Detection

- Hybrid gas and particulate sensors for fire detection
  - Knowledge of spacecraft fire signatures

## Fire Suppression

- Common portable fire extinguisher for exploration
  - Relevant for elevated oxygen conditions, varying size of vehicle

## Post-fire response

- Hybrid gas and particulate sensors for post-fire monitoring
- Post-fire cleanup technology (Smoke-Eater)
- Combustion Product Monitor

## System Demonstration

• Demonstration of end-to-end fire detection, suppression, and post-fire cleanup technologies

# Conclusions

- Microgravity fire behavior remains poorly understood and a significant risk for spaceflight
- An experiment is under development that will provide the first real opportunity to examine this issue focusing on two objectives
  - Material Flammability
  - Flame Spread
- 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 work towards its implementation.
  - Pressure Rise prediction and Modeling
  - Sample Material Selection
  - Supportive Experiments Ground, Drop-Tower, Parabolic Flights, ISS
- This experiment will be a landmark for spacecraft fire safety with the data and subsequent analysis providing much needed verifications of spacecraft fire safety protocol for the crews of future exploration vehicles and habitats.