DTU Library

Fire Safety in Space

Beyond Flammability Testing of Small Samples

Jomaas, Grunde

Publication date:
2014

Document Version
Peer reviewed version

St. Petersburg July 28, 2014

Fire Safety in Space –

Beyond Flammability Testing of Small Samples

GRUNDE JOMAAS

ASSOCIATE PROFESSOR

DTU CIVIL ENGINEERING

Goals for ISS and Space Design

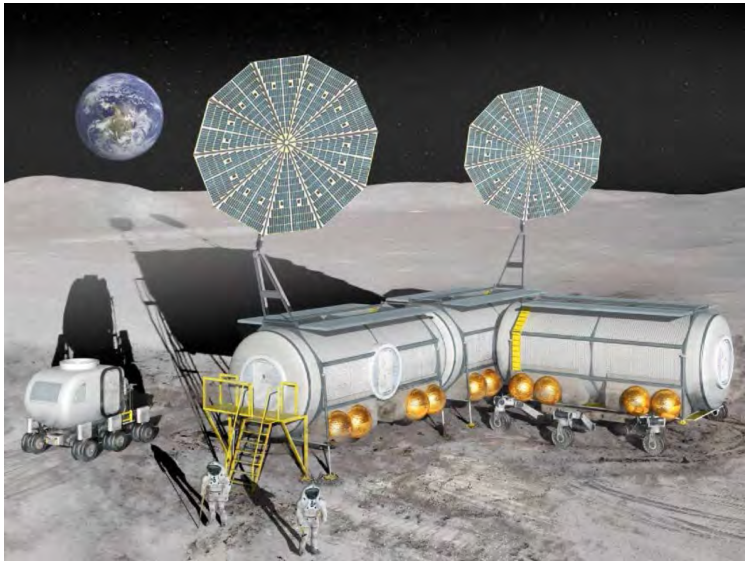
- Safety for launch, personnel, hardware, uninvolved public
- Identify, control and document hazards
- Enable informed programmatic decisions
- Handle situations and continue successfully
- Redundancy
  - CO_2 removal system
  - Atmosphere Control System(ACS)
  - Oxygen supply system
- Robust, yet versatile
- 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

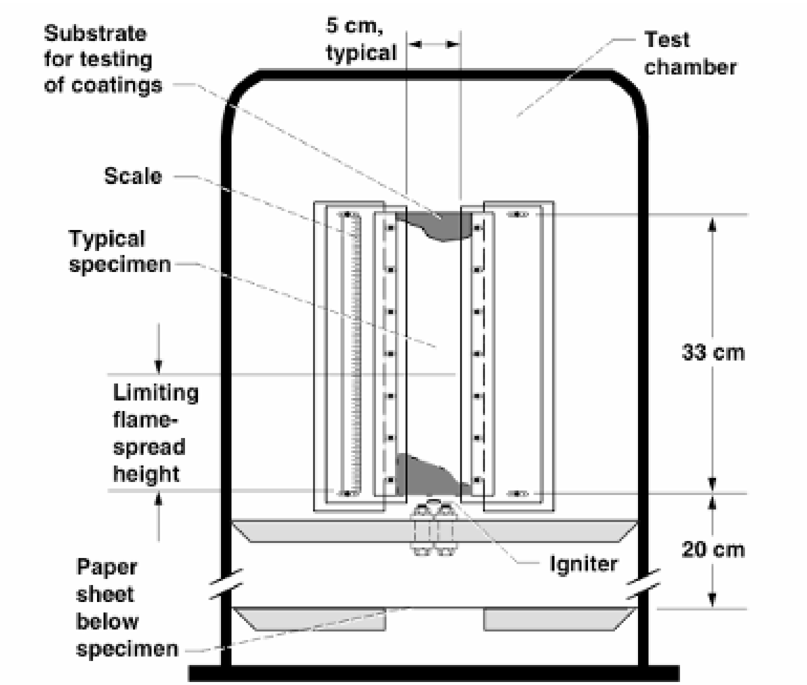
Progress related challenges



- 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



Test 1 Apparatus

- 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 at which material passes Test 1
- Flammability limits determined by this test are <u>strongly influenced by natural 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?*

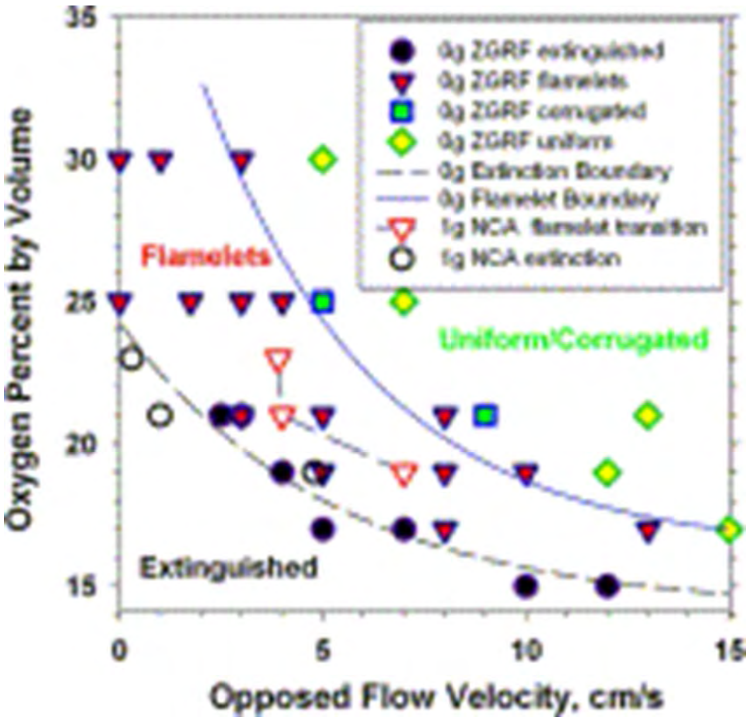
Material Flammability

- Mostly based on a “Worst Case Scenario” Test
- NASA Test 1

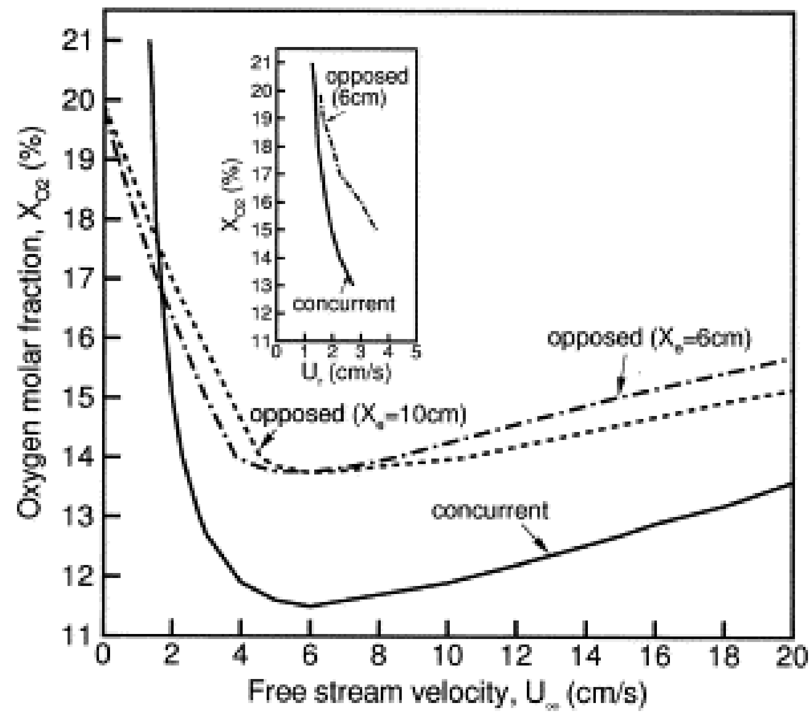
Challenges

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

Can it be “Worse” than Test 1?



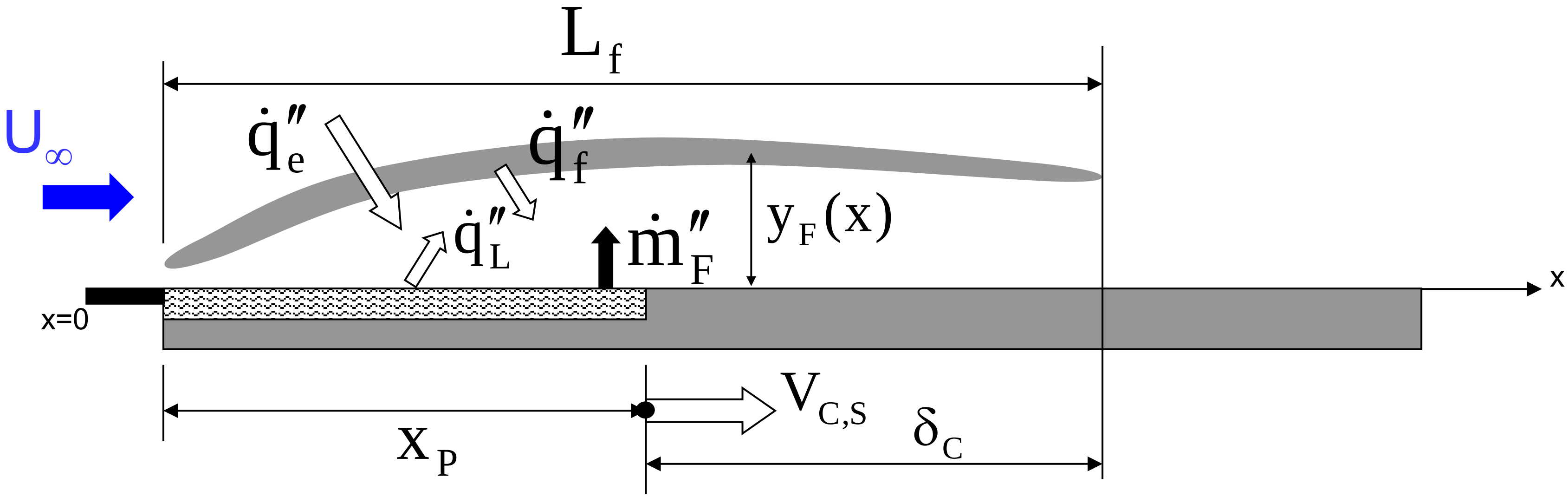
S.L. Olson, F.J. Miller, S. Jahangirian, I.S. Wichman, Combustion and Flame, 2009

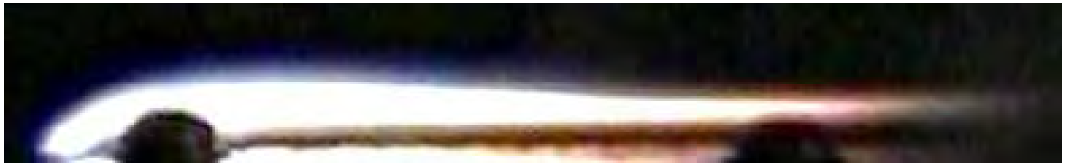


A. Kumar, H.Y. Shih, J.S. T’ien, Combustion and Flame, 2003

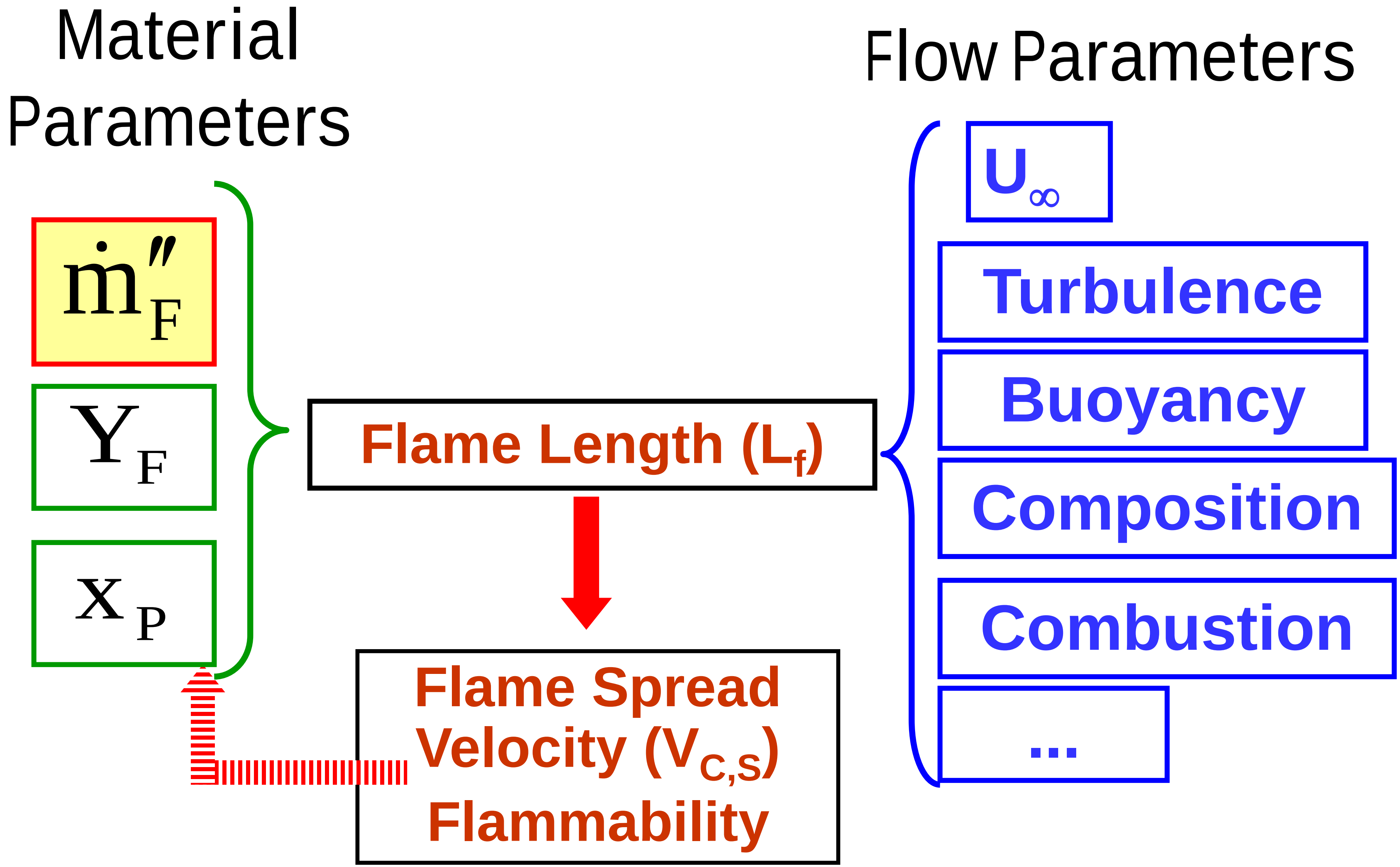
Differences

Understanding Flammability –
Co-current flame spread

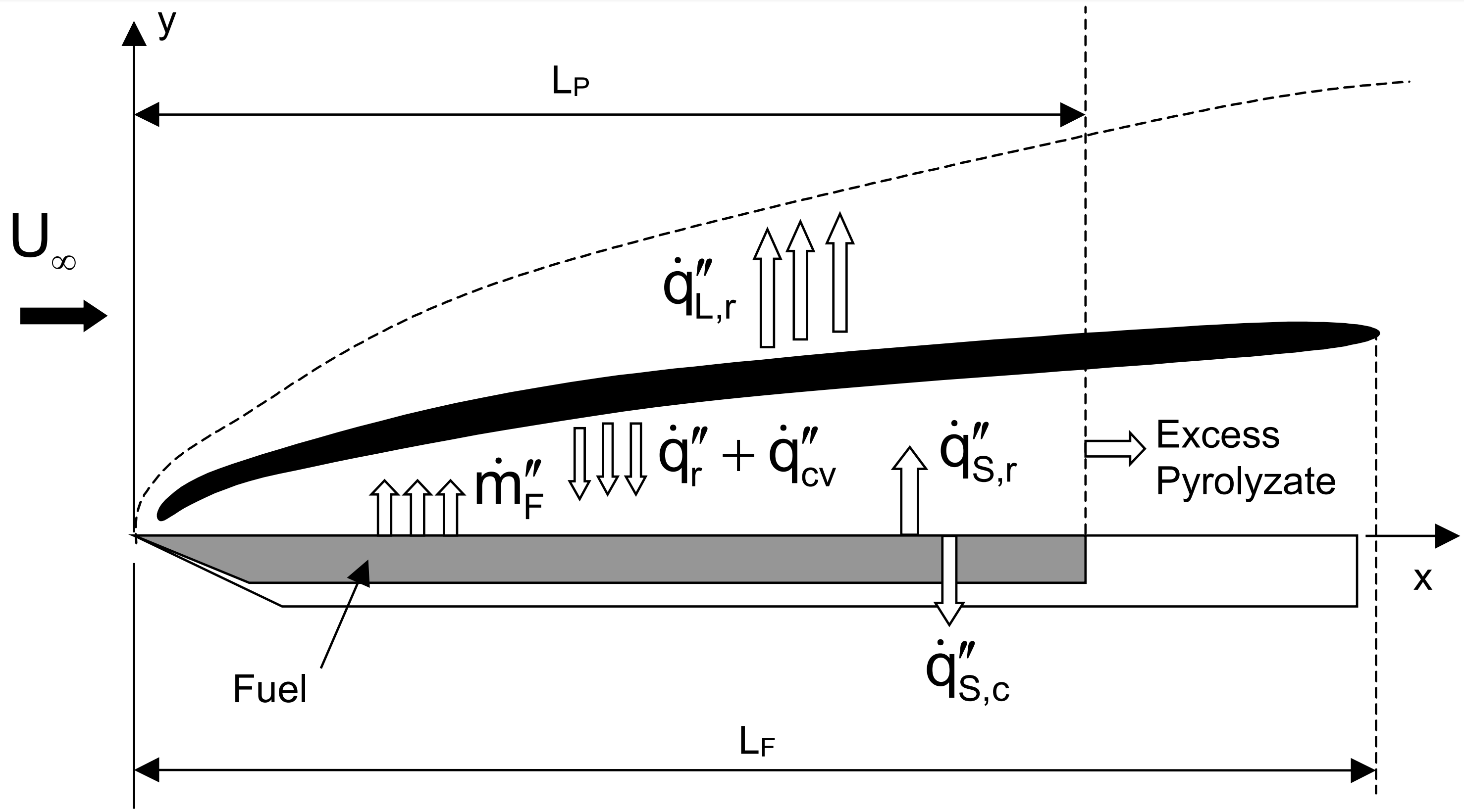




Relevant Parameters



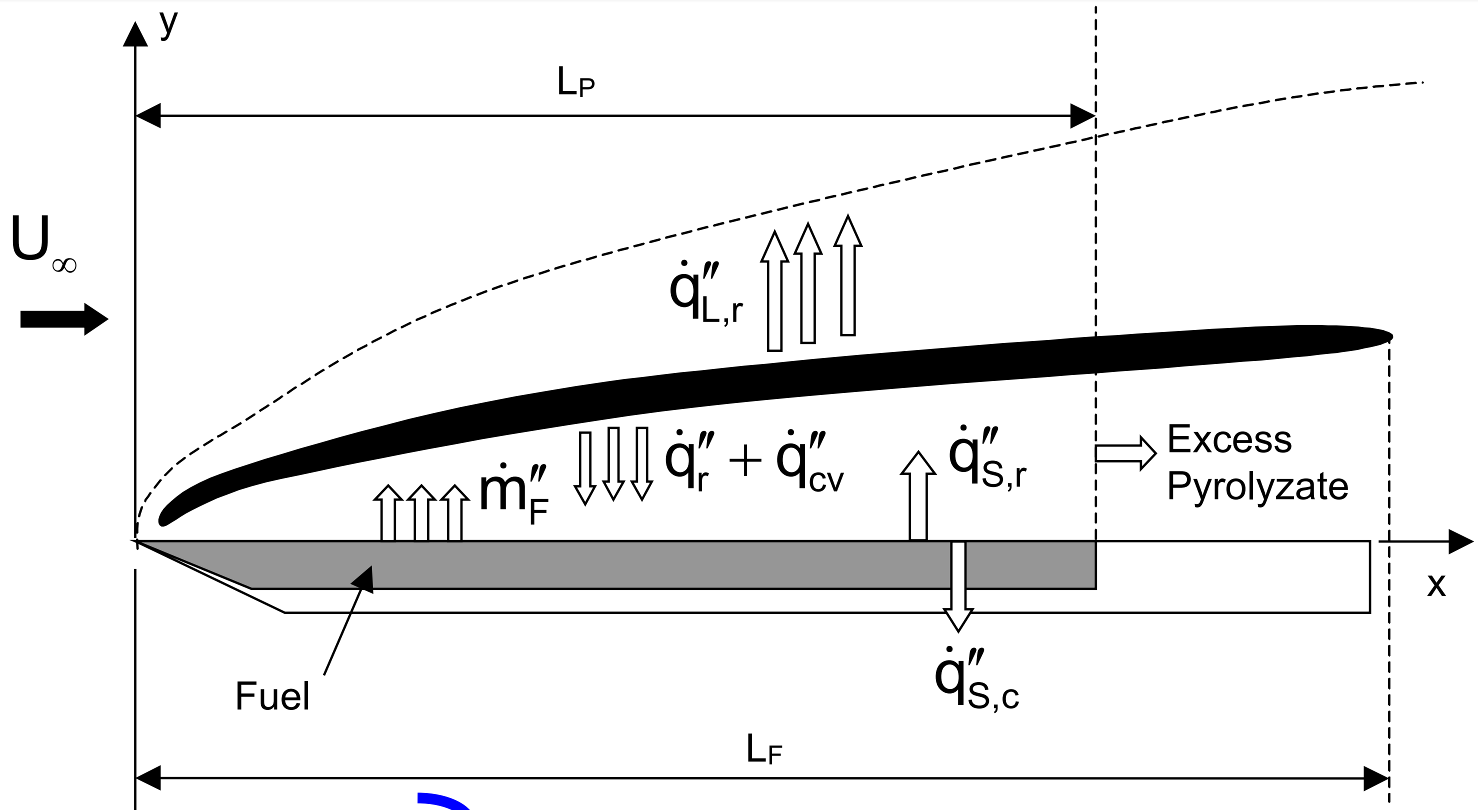
The Emmons Solution (I)



$$f = \frac{\psi}{(x/Re)^{1/2}} \qquad \beta = \frac{Z_i - Z_{i,0}}{Z_{i,\infty} - Z_{i,0}} \qquad \eta = \frac{1}{2}\left(\frac{Re}{x}\right)^{1/2} \int_0^y \rho dy$$

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

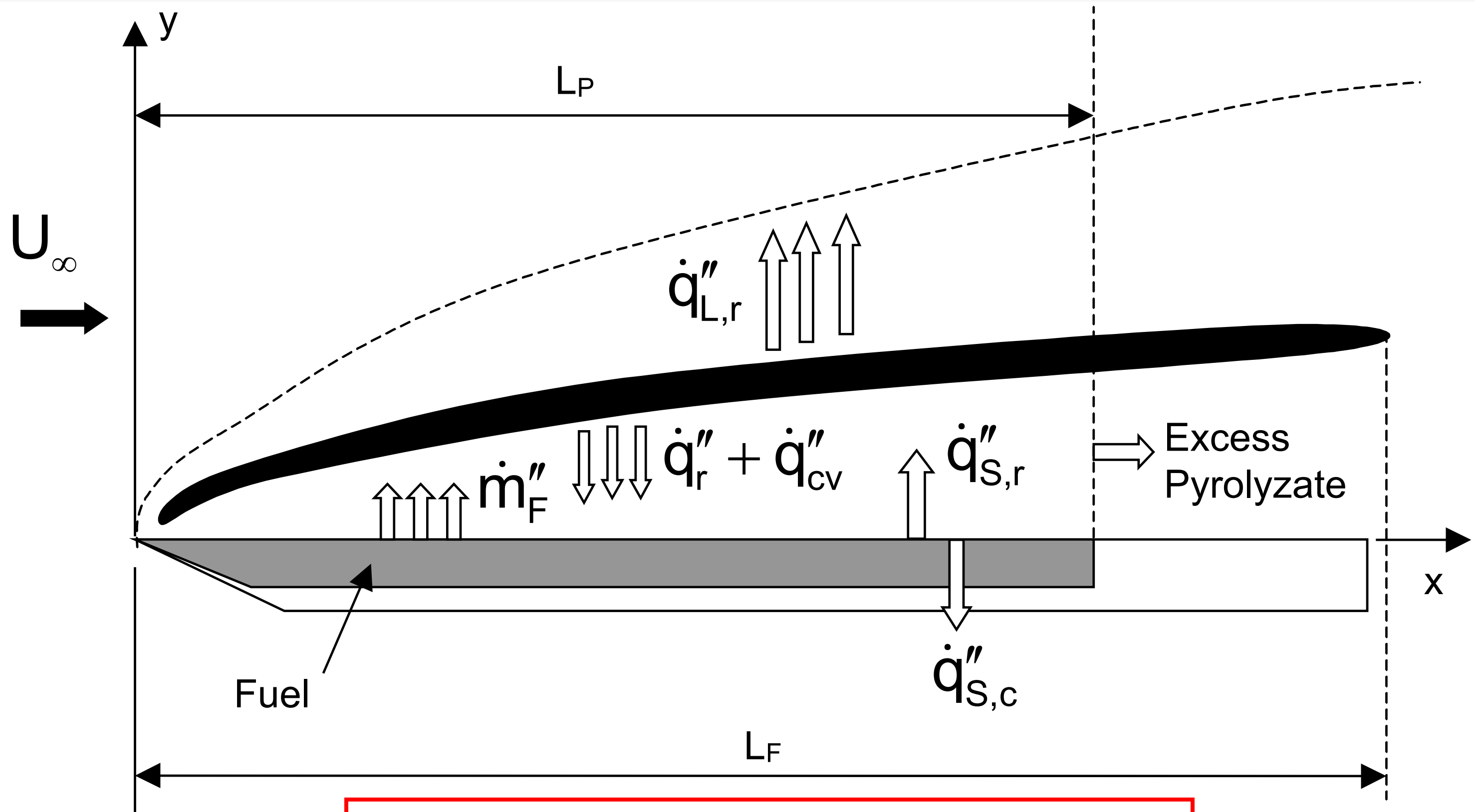
The Emmons Solution (II)



$$\left.\begin{aligned} f''' + f \cdot f'' = 0 \\ \beta'' + f \cdot \beta' = 0 \end{aligned}\right\} \quad \begin{aligned} &\eta = 0 \quad , \quad f' = 0 \quad , \quad \frac{f}{f''} = -\frac{B}{2} \quad , \quad \beta = 0 \\ &\eta \to \infty \quad , \quad f' = 2 \quad , \quad \beta = 1 \end{aligned}$$

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

The Emmons Solution (III)



$$B = \frac{\Delta H_C Y_{O,\infty} - C(T_S - T_\infty)}{\Delta H_P + Q}$$

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

The Mass Transfer Number

Adiabatic

$$B_A = \frac{\Delta H_C Y_{O_2,\infty} - Cp_\infty (T_W - T_\infty)}{\Delta H_P}$$

Property of the fuel and oxidizer, therefore easy to evaluate

Combustion Efficiency

$$B_T = \frac{(1-\chi)(\Delta H_C Y_{O_2,\infty}) - Cp_\infty (T_W - T_\infty)}{\Delta H_P + Q}$$

Losses

Variable, depending on the specific burning conditions, therefore 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

<u>Project Objective:</u>

- 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

<u>Experiment Objective:</u>

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

Controlled burns of structures

Naval Research Laboratory Ex-USS Shadwell

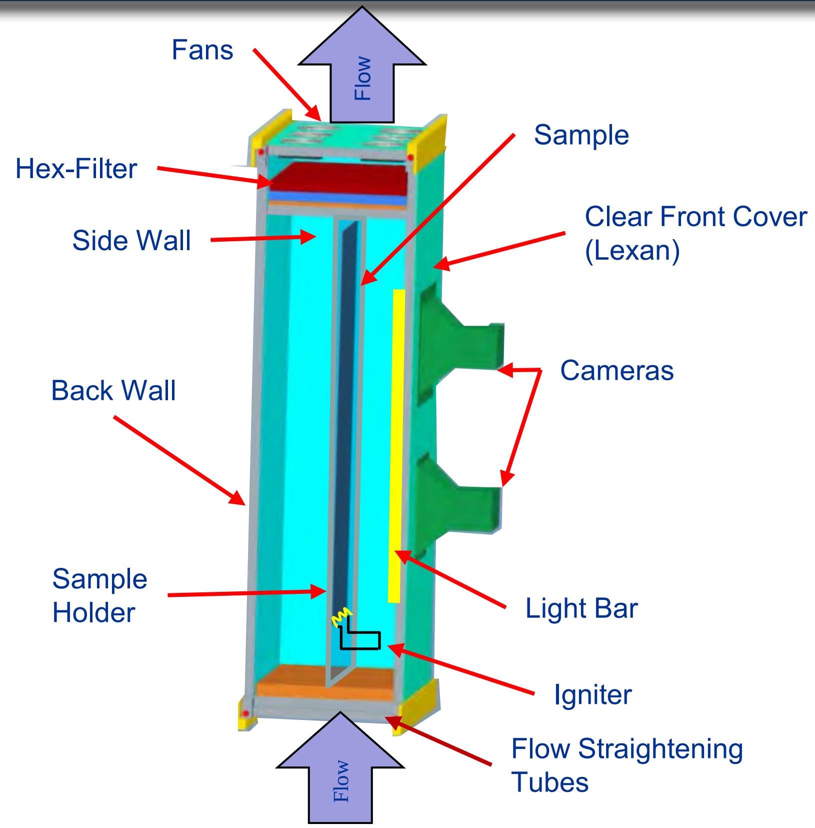
ESA's ATV approaching the ISS

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



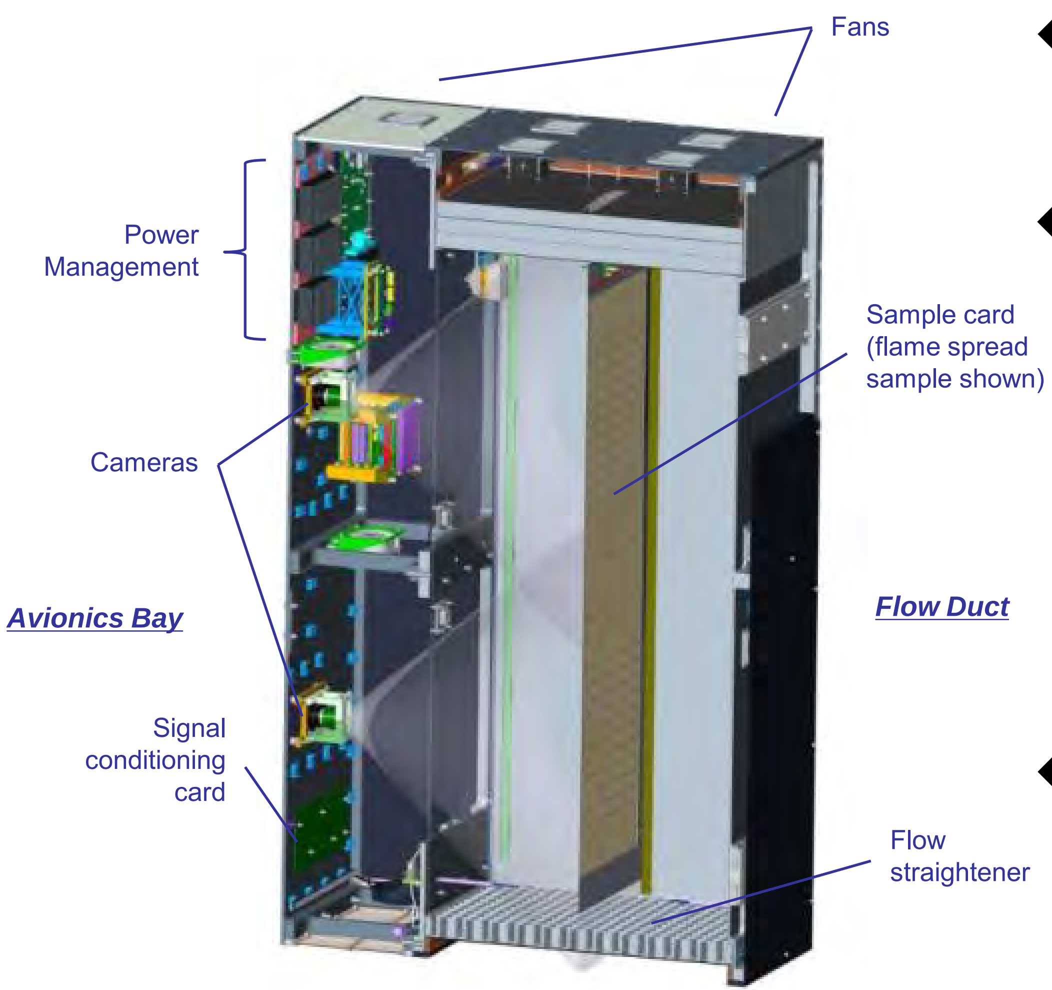
Details of experiment flow duct approximate size: 20” x 20” x 44”

- “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)
  2. 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

Design choices driving simplified concept →

- 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

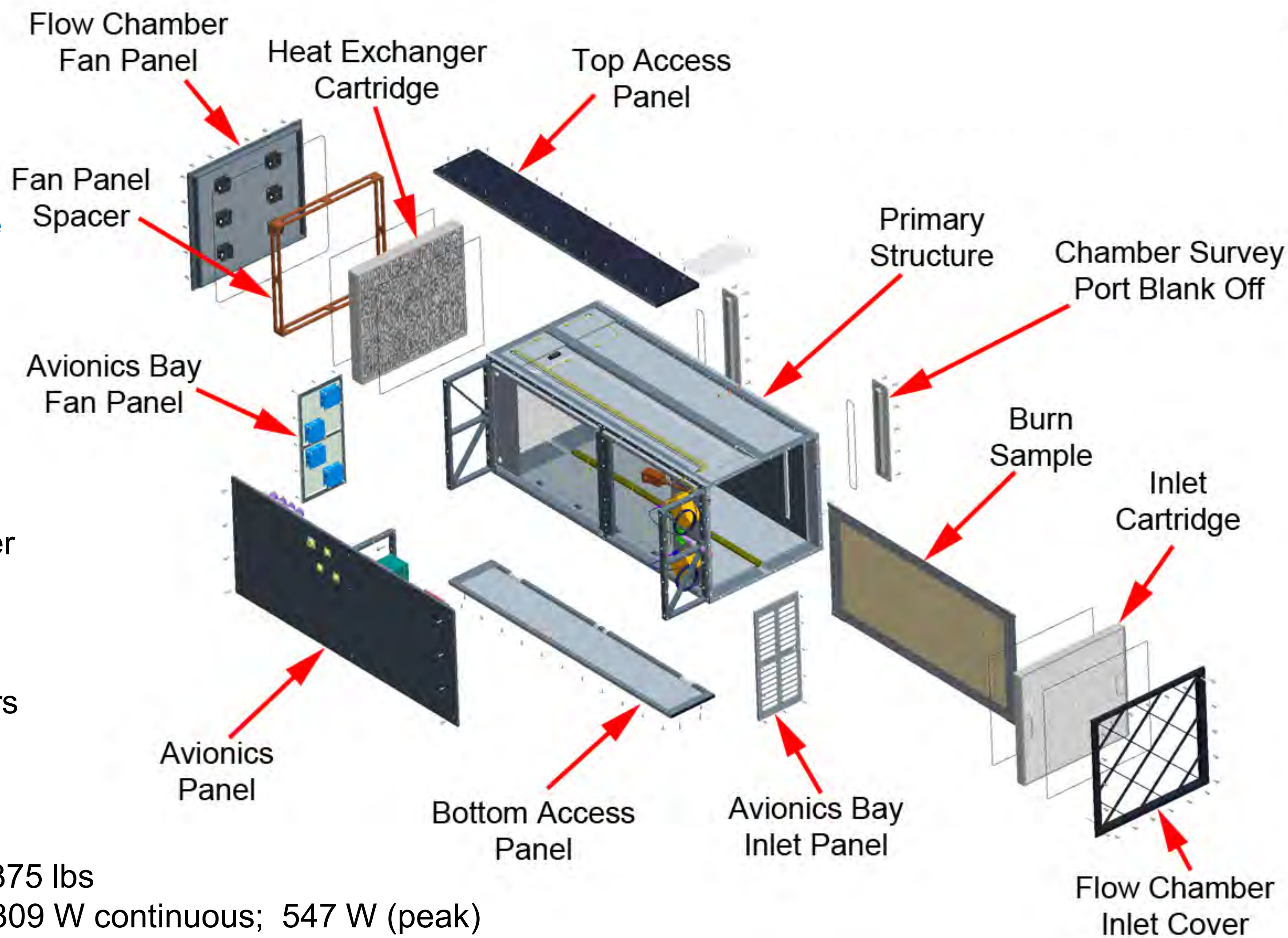


- **Two major assemblies**
  - Avionics Bay
  - Flow Duct
- **Nine separate hardware "products"**
  - Sample card
  - Flow control
  - Power management system
  - Igniter
  - Signal conditioning
  - Cameras/vision
  - Instrumentation
  - Processor stack
  - Data Acquisition
- **Hardware Products evaluated by Tabletop Reviews prior to hand-off to Assembly, Integration, and Test**

Saffire Flight Unit Structure

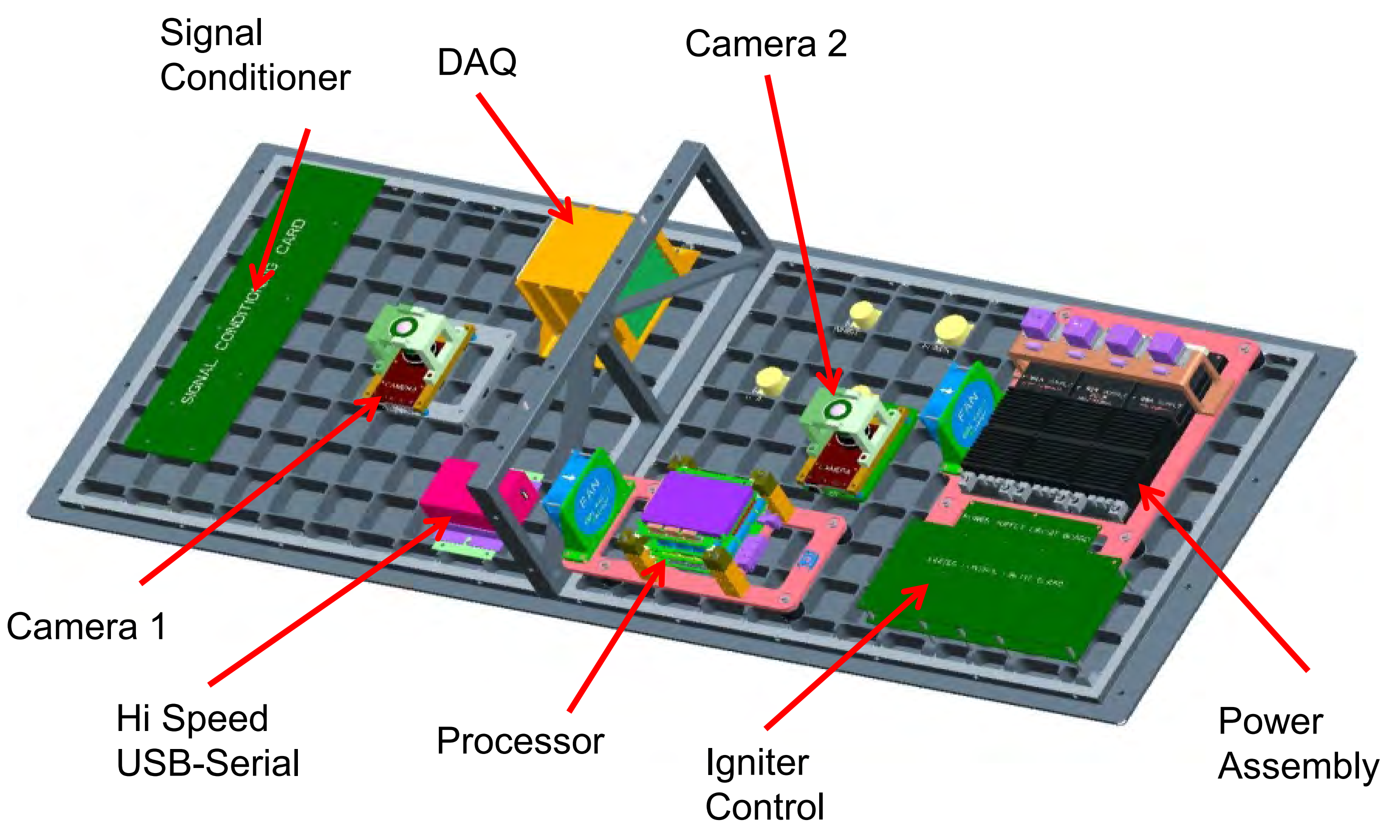
<u>Products</u>

1. Primary Structure
2. Sample Card
3. Flow Control
4. Thermal/Fluids
5. Power
6. Igniter Control
7. Processor
8. Instrumentation
9. Signal Conditioner
10. Vision system
11. DAQ
12. USB
13. Cables/connectors
14. Software



- Maximum mass: 375 lbs
- Maximum power: 309 W continuous; 547 W (peak)
- Dimensions: 35.3” x 21.0” x 52.5”

Saffire Avionics Plate

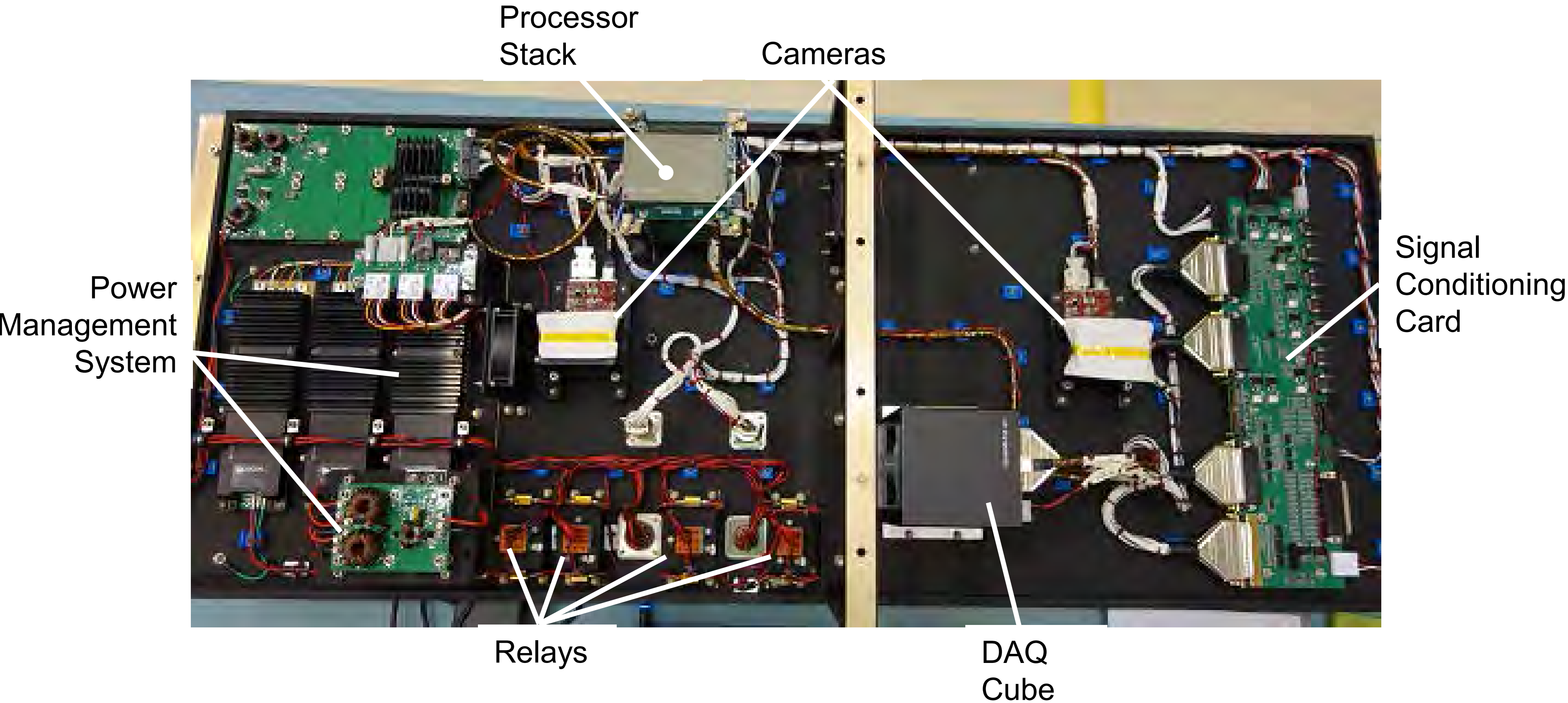


Products

1. Primary Structure
2. Sample Card
3. Flow Control
4. Thermal/Fluids
5. Power
6. Igniter Control
7. Processor
8. Instrumentation
9. Signal Conditioner
10. Vision system
11. DAQ
12. USB
13. Cables/connectors
14. Software

Assembly and Integration Status
Avionics Panel Assembly

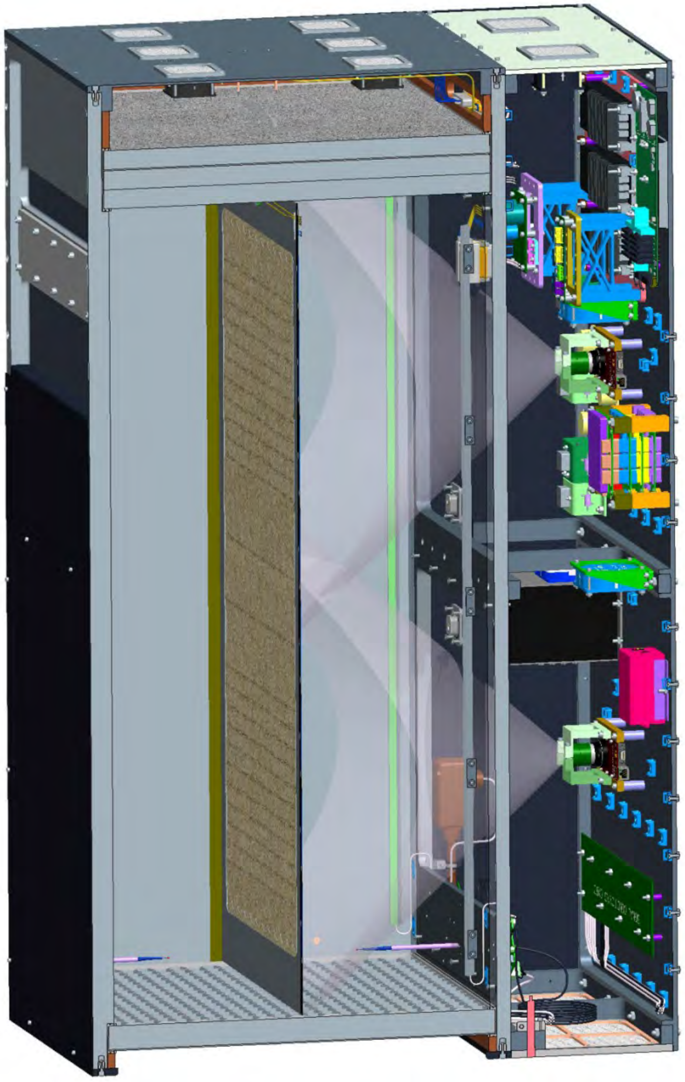
- Assembly and functional testing of Saffire-I, II, and III avionics panels completed in July 2014
- Tests of the low and high speed serial Cygnus interface showed compliance with our Saffire-Cygnus serial communications interface requirements.



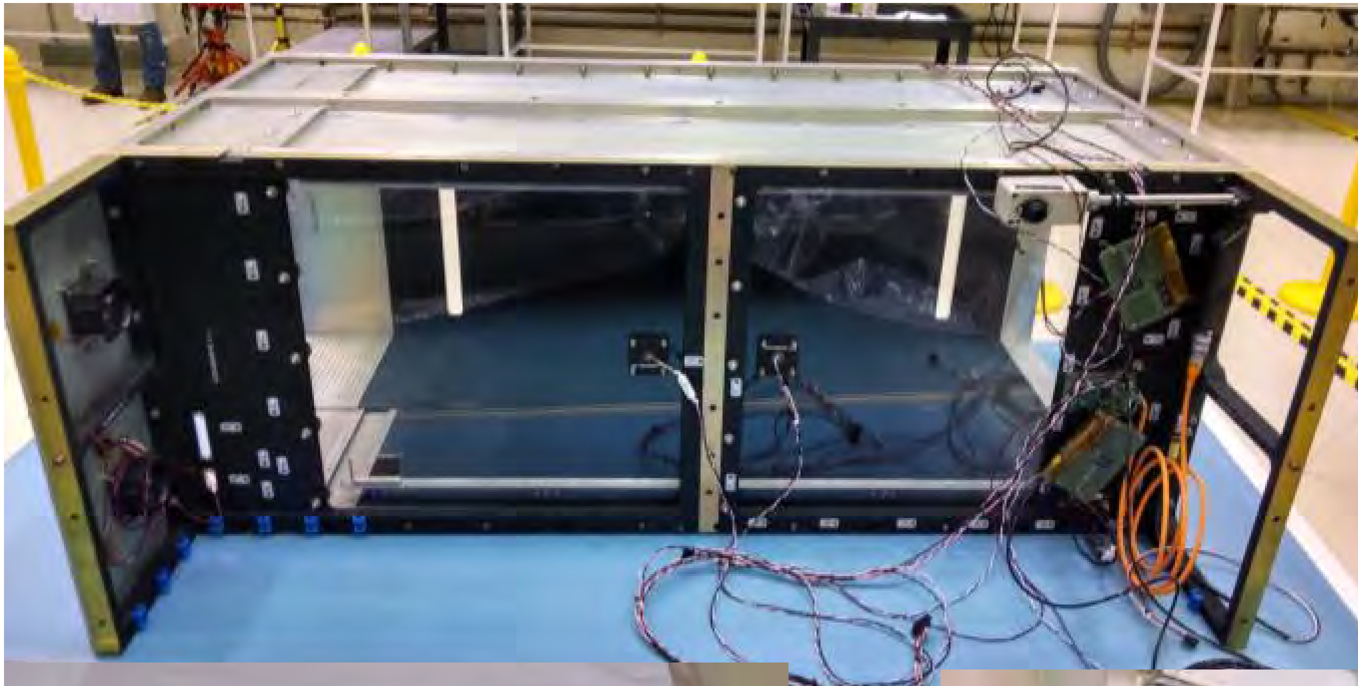
- Avionics panel is 1.3 m long by 0.5 m wide

Flight tests

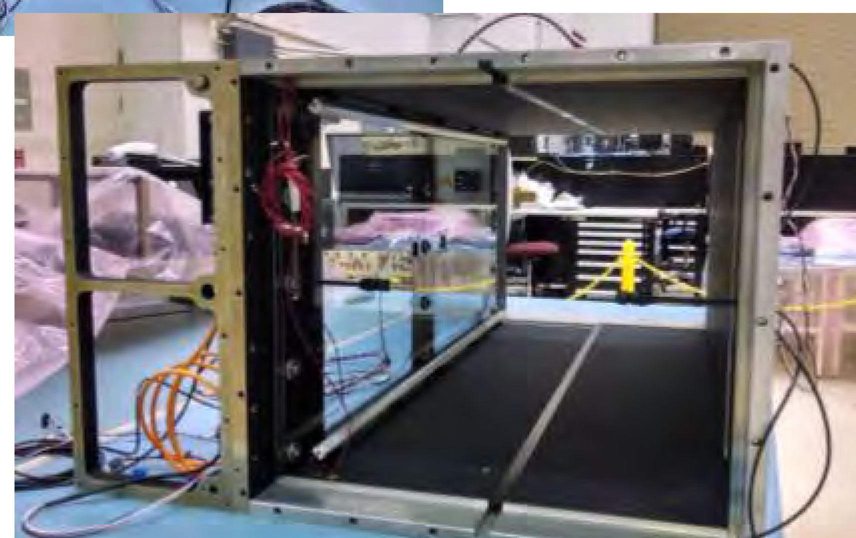
1. **Large Flame Spread sample**
   - Orbital-5: July 24, 2015
2. **Material Flammability samples**
   - Orbital-6: January 4, 2016
3. **Large Flame Spread Sample**
   - Orbital-7: June 19, 2016



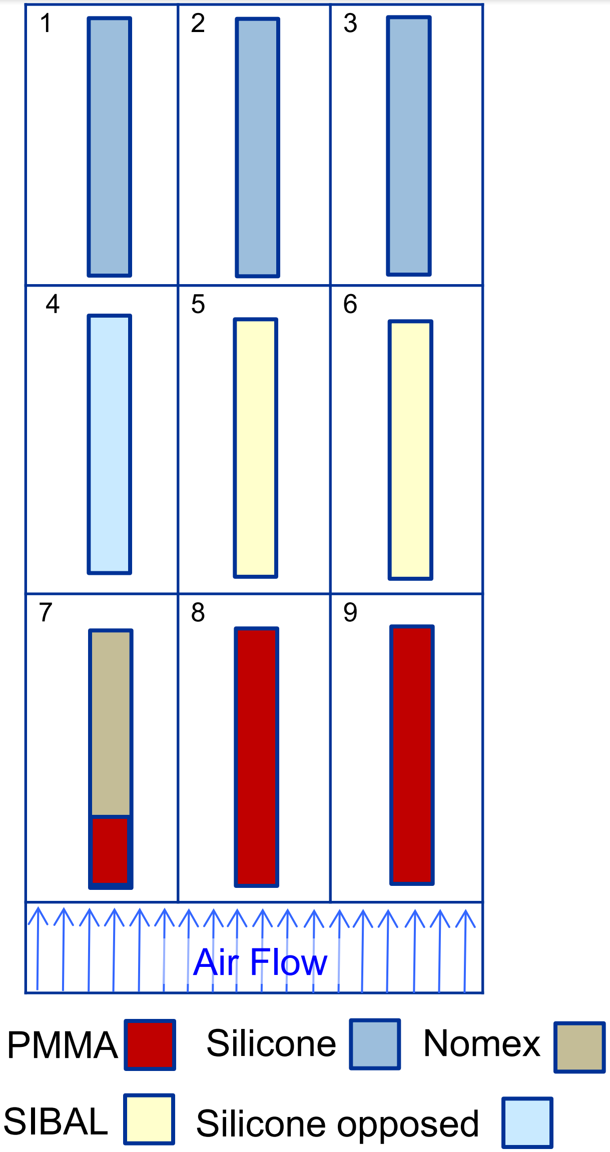
Assembly and Integration Status
Flow Duct Assembly



- ***Flow duct instrumentation***
  - *Radiometers*
  - *O_2 sensor*
  - *CO_2 sensor*
  - *Pressure Transducer*
  - *Anemometers*
  - *Thermocouples*



Saffire-2 Sample Details



Sample #	Material	Sample Thickness	Air Flow (cm/s)	Igniter Position
Saffire-2-S1	Silicone (Flammability limit 1)	0.25 mm (0.010”)	20	Bottom
Saffire-2-S2	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	Top
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
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

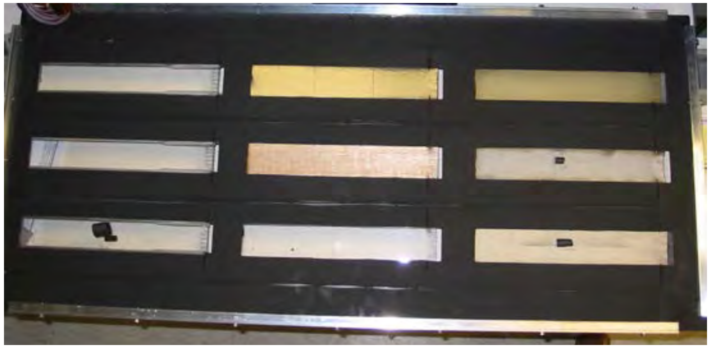
Science Status
Saffire-II Sample Card

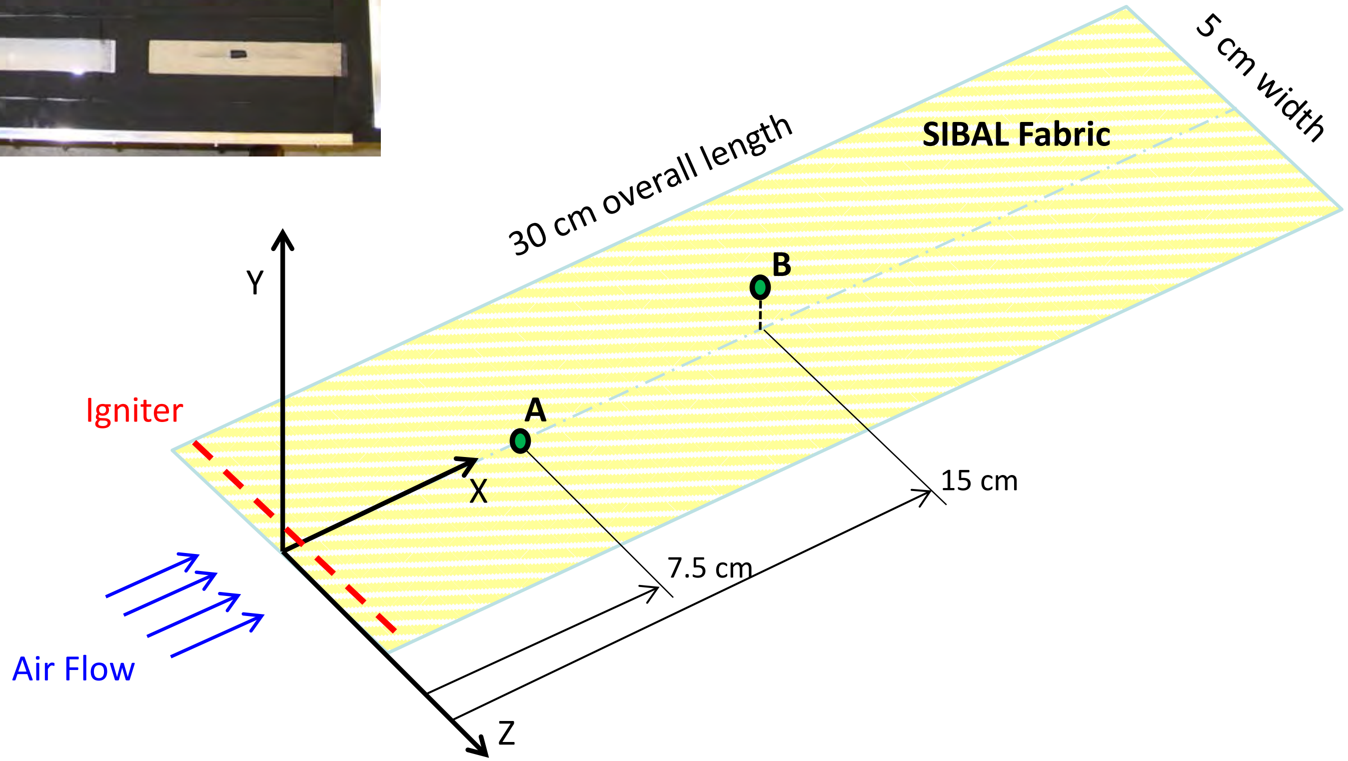
- Populated and wired sample card for Saffire-II

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

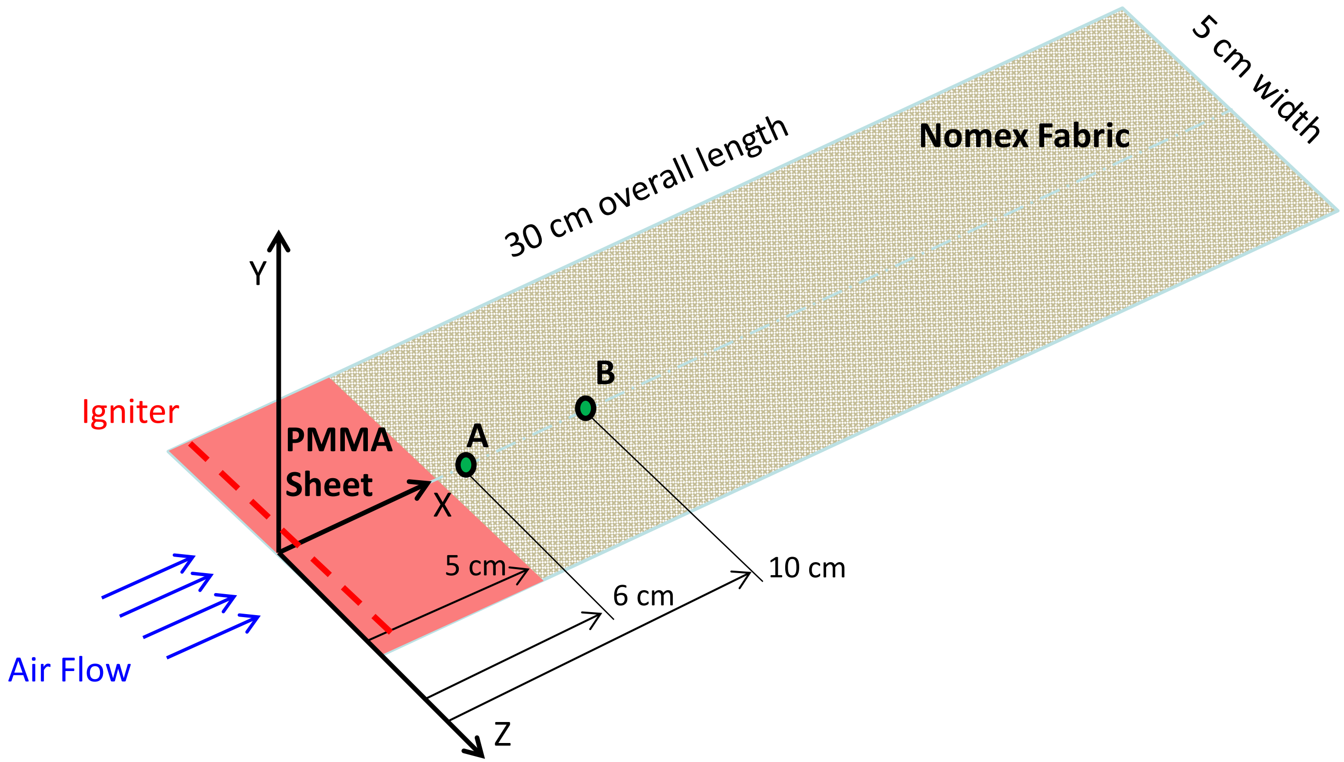
Flow

Saffire-2 Sample 5 and Sample 6 Details



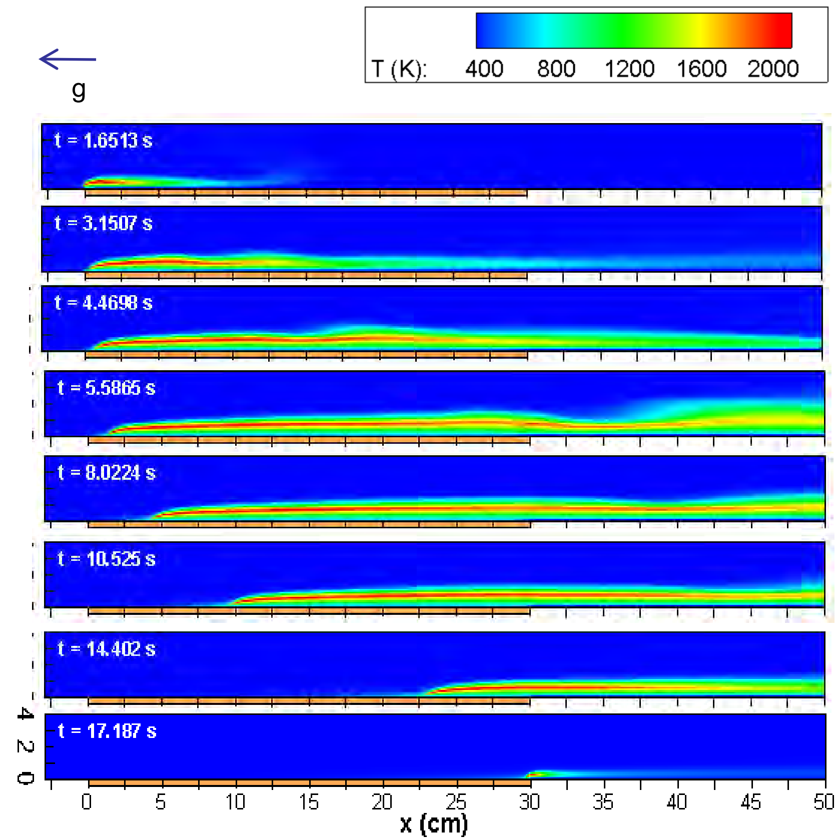


Saffire-2 Sample S7 (Transition: PMMA to Nomex) Details



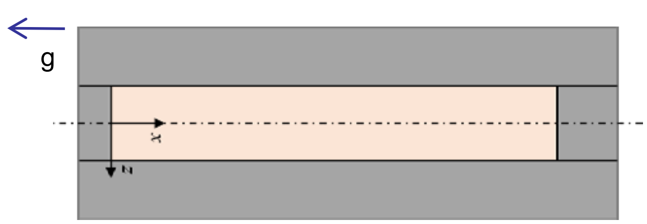
Science Status
Modeling

- 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 6th 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.

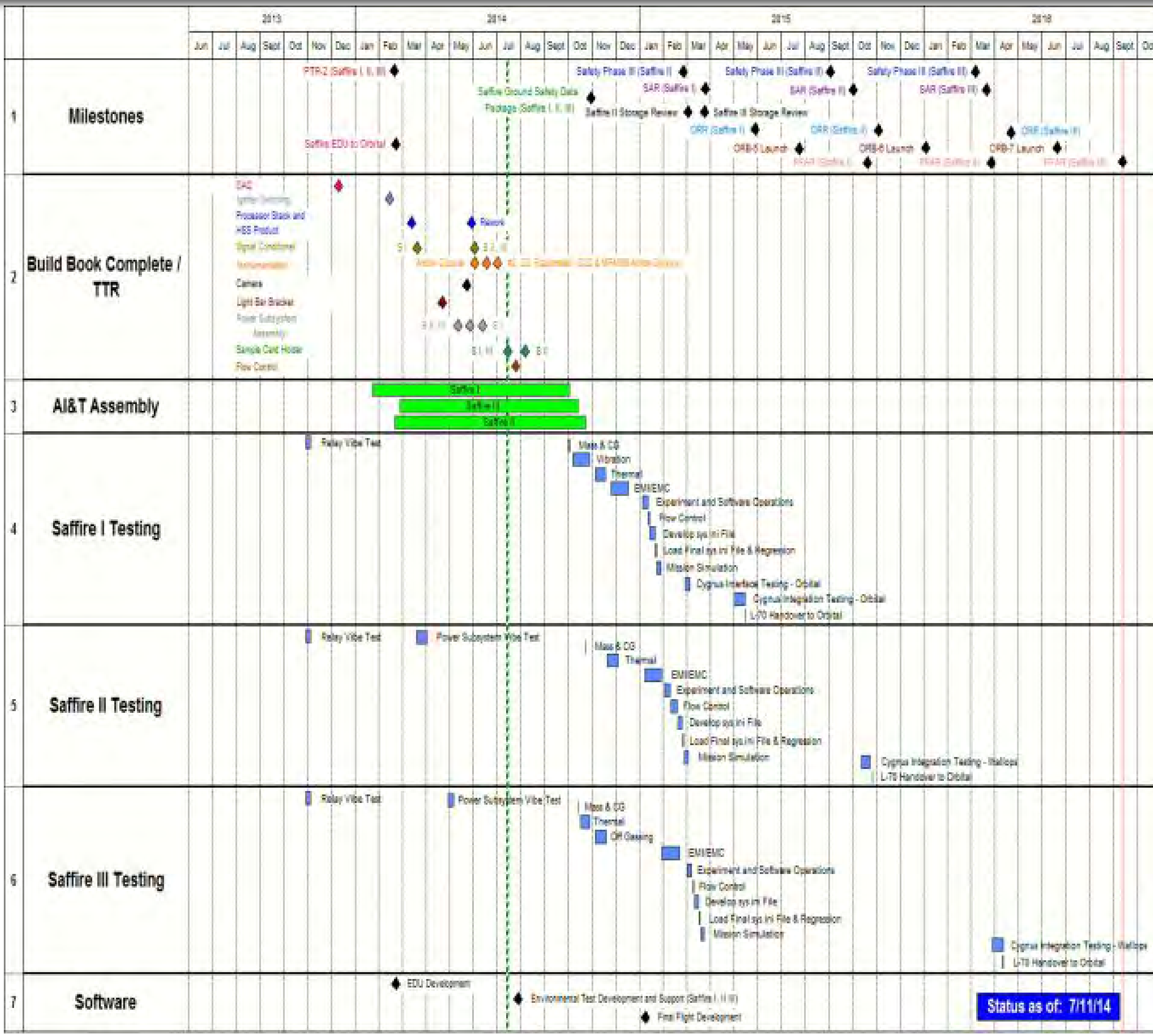


Temperature along center plan (colors) vs. time (top to bottom) for a buoyant flow condition. *(In low-g, Saffire conditions will be in forced flow.)*

Buoyant flow sample is 5 cm wide by 30 cm long, sandwiched by metal plates



Saffire Development Schedule



Milestone	Date
Software TTR #1 – Environmental Test S/W (UID 4752)	**7/28/14**
Saffire-I Assembly Complete (UID 4123)	10/2/14
Saffire-III Assembly Complete (UID 4151)	10/14/14
Saffire-II Assembly Complete (UID 4137)	10/23/14
Ground Safety Data Package Submit (UID 2884)	**10/31/14**
Saffire-III Offgas Testing Complete (UID 4211)	11/18/14
Saffire-I Environmental Testing Complete (UID 4177)	12/17/14
Software TTR #2 – Final SW Version (UID 4751)	**1/2/15**
Saffire-I Phase II Functional Testing Complete (UID 4179)	1/28/15
Saffire-I ISS Phase III Flight Safety Review (UID 2882)	**2/27/15**
Cygnus Interface Testing at Orbital Start (UID 4186)	3/2/15
Saffire-I SAR (UID 2883)	**3/25/15**
Saffire-I Ship to Wallops (UID 6257)	5/1/15
Saffire-I Cygnus Integration Testing at Wallops Start (UID 6258)	5/4/15
Saffire-I Launch minus 70 day Turnover (UID 6259)	5/15/15

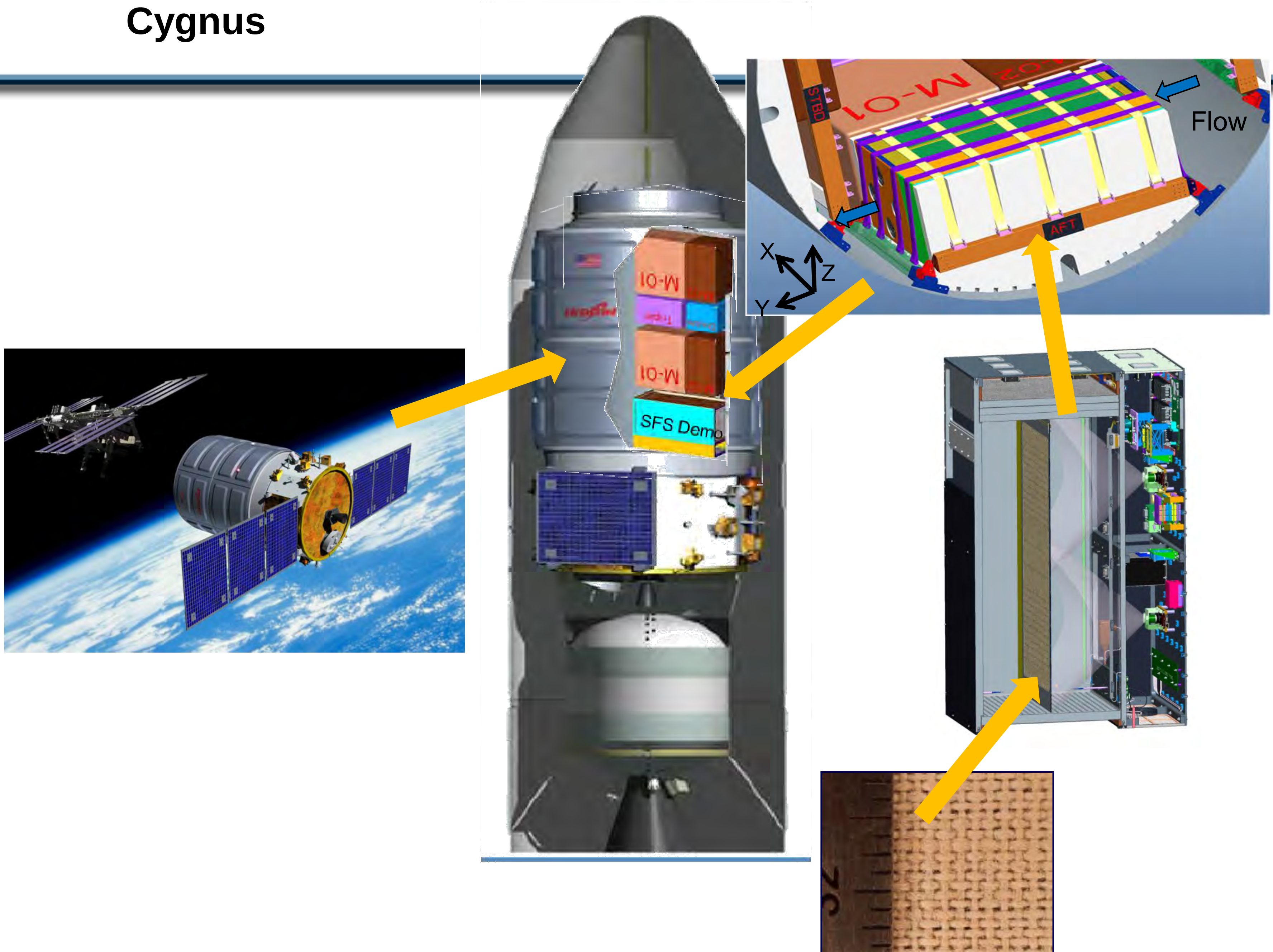
Orbital Cygnus

Orbital Cygnus

Orbital Cygnus

Orbital Cygnus

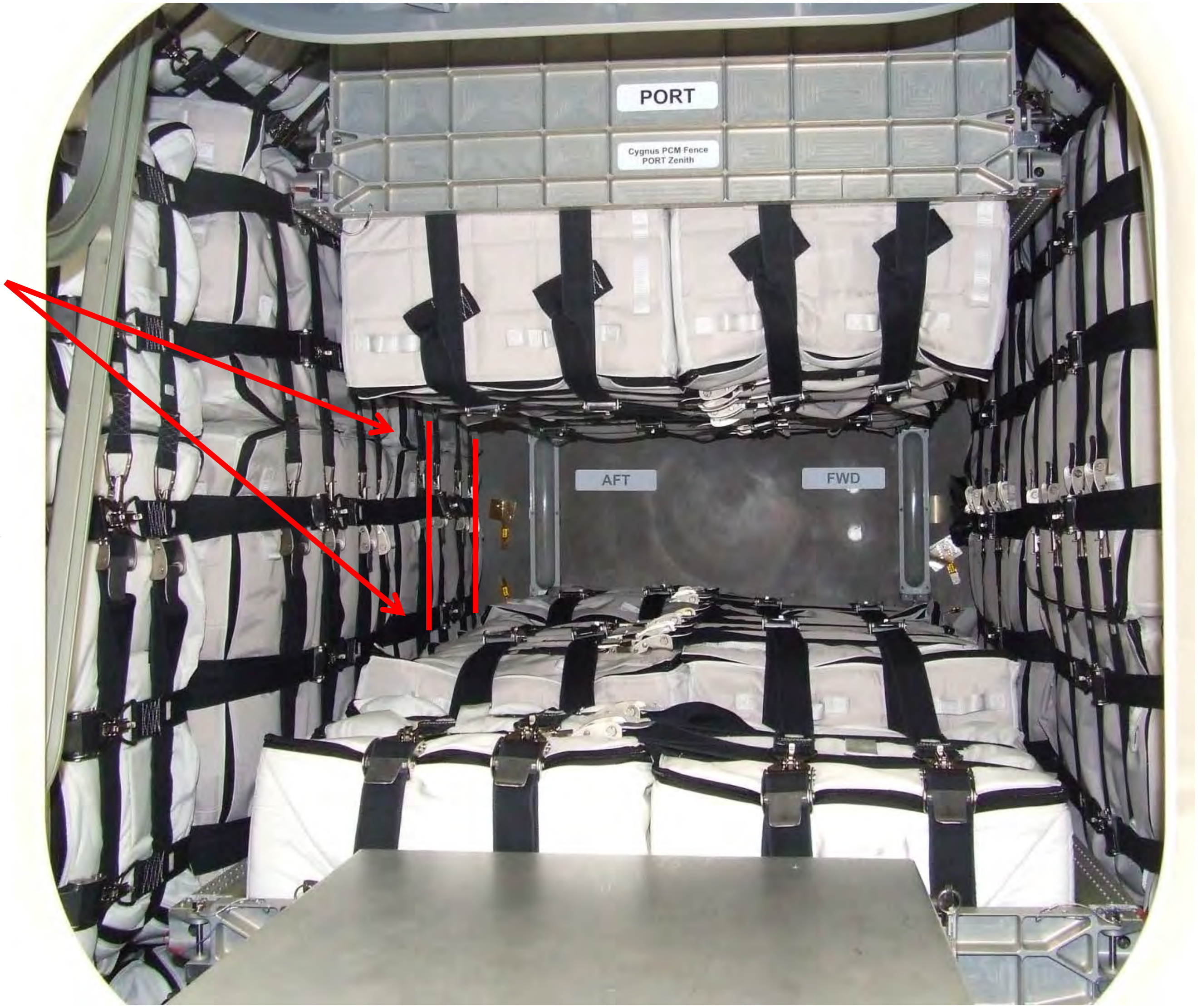
Cygnus



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

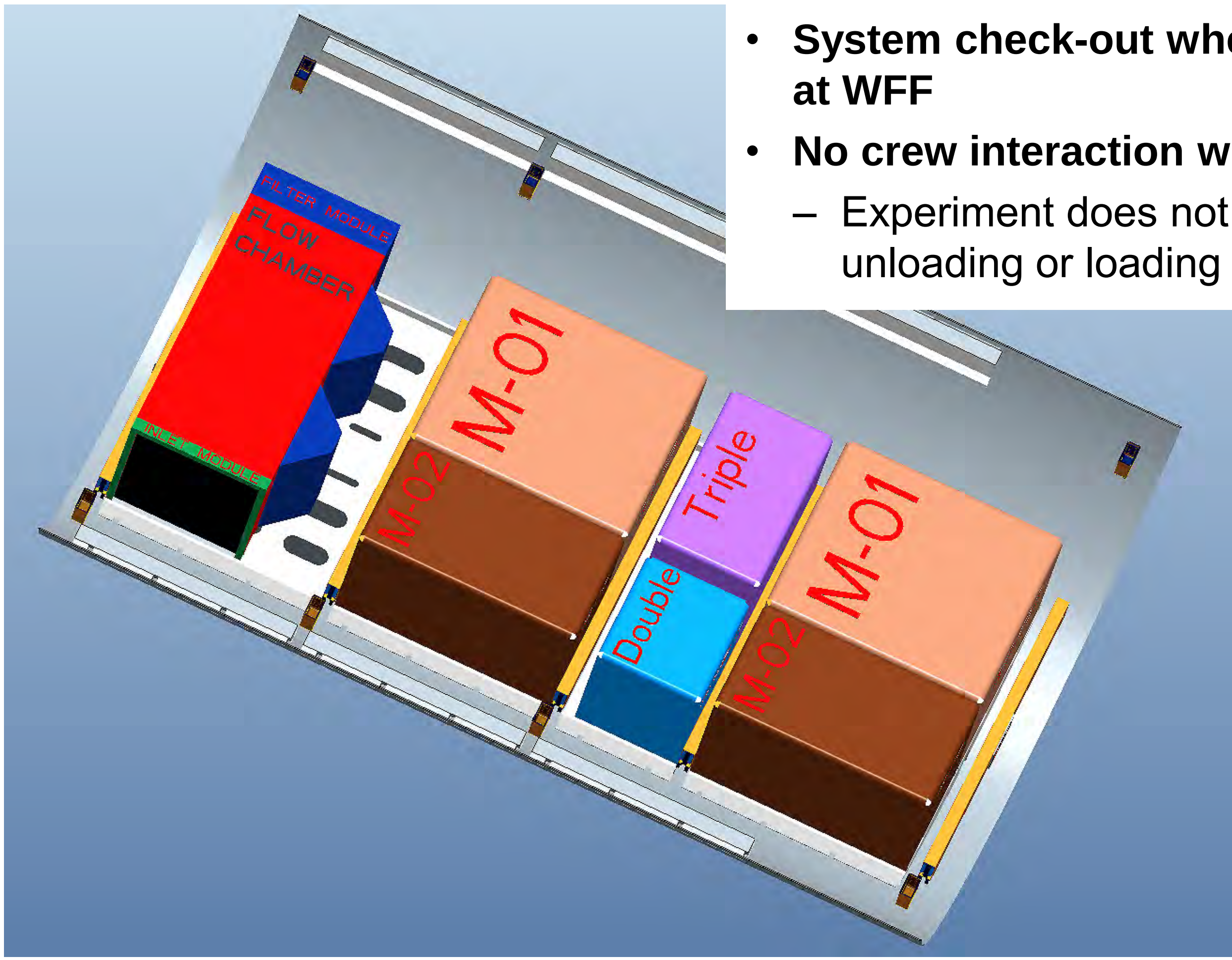
Proposed location of SFS Demo Experiment

- *Experiment would use standard straps and replace cargo bags.*



Experiment Configuration

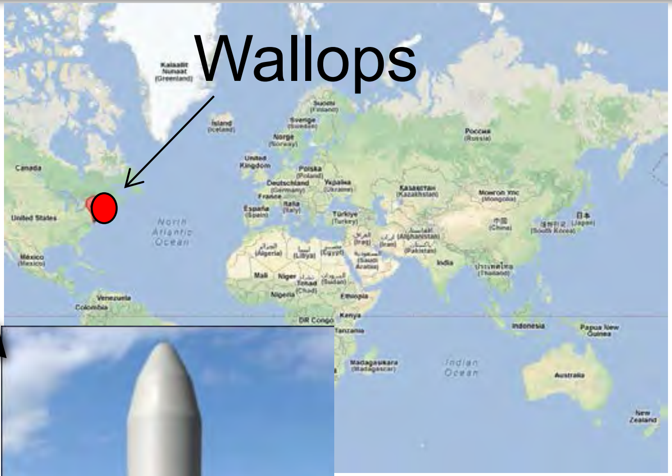
- **Experiment replaces an M-01 and M-02 bag**
- **Fully assembled and installed into the PCM at Wallops Flight Facility (WFF)**
  - Power and communication cables
- **System check-out when attached to Service Module at WFF**
- **No crew interaction with the experiment**
  – Experiment does not need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

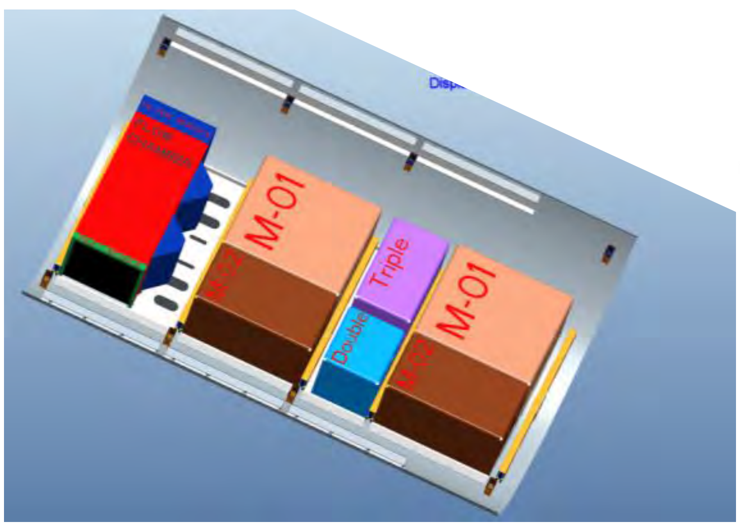
Antares Launch

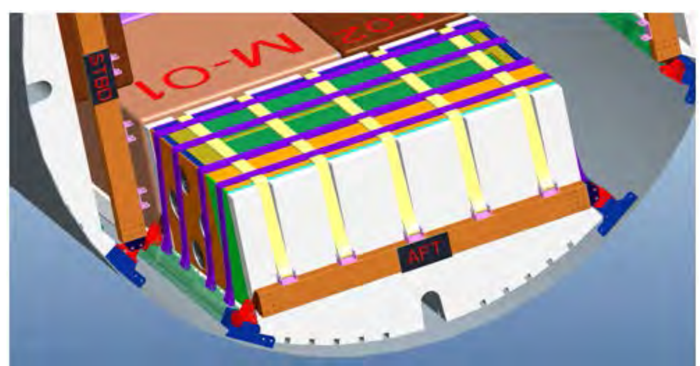
Mission Concept

Cygnus approaching ISS

Unpack cargo, reload with trash

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

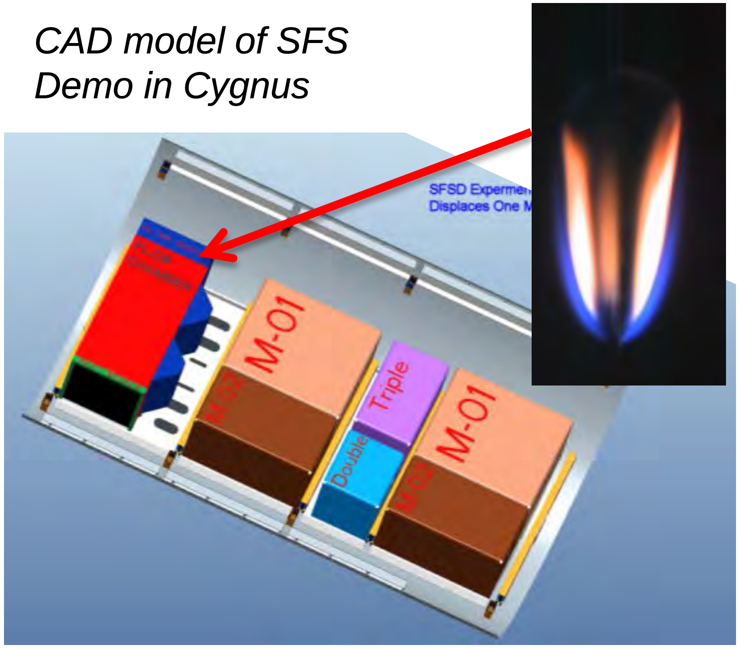




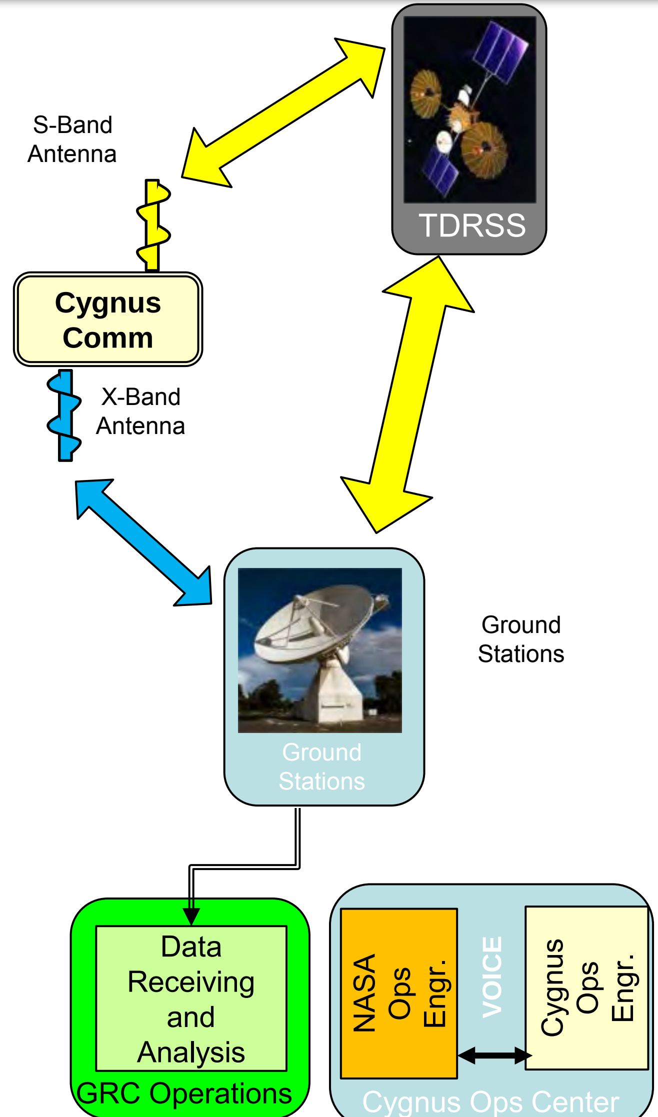
Check-out SFS Demo experiment

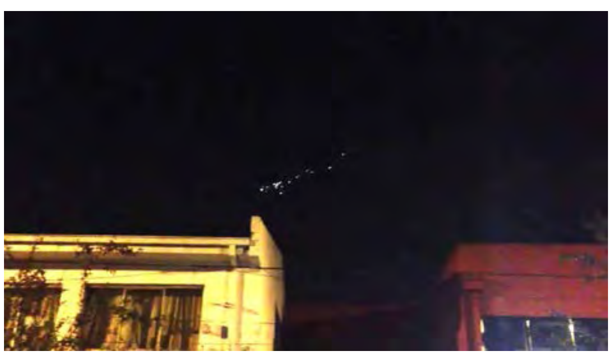
Mission Concept

CAD model of SFS Demo in Cygnus

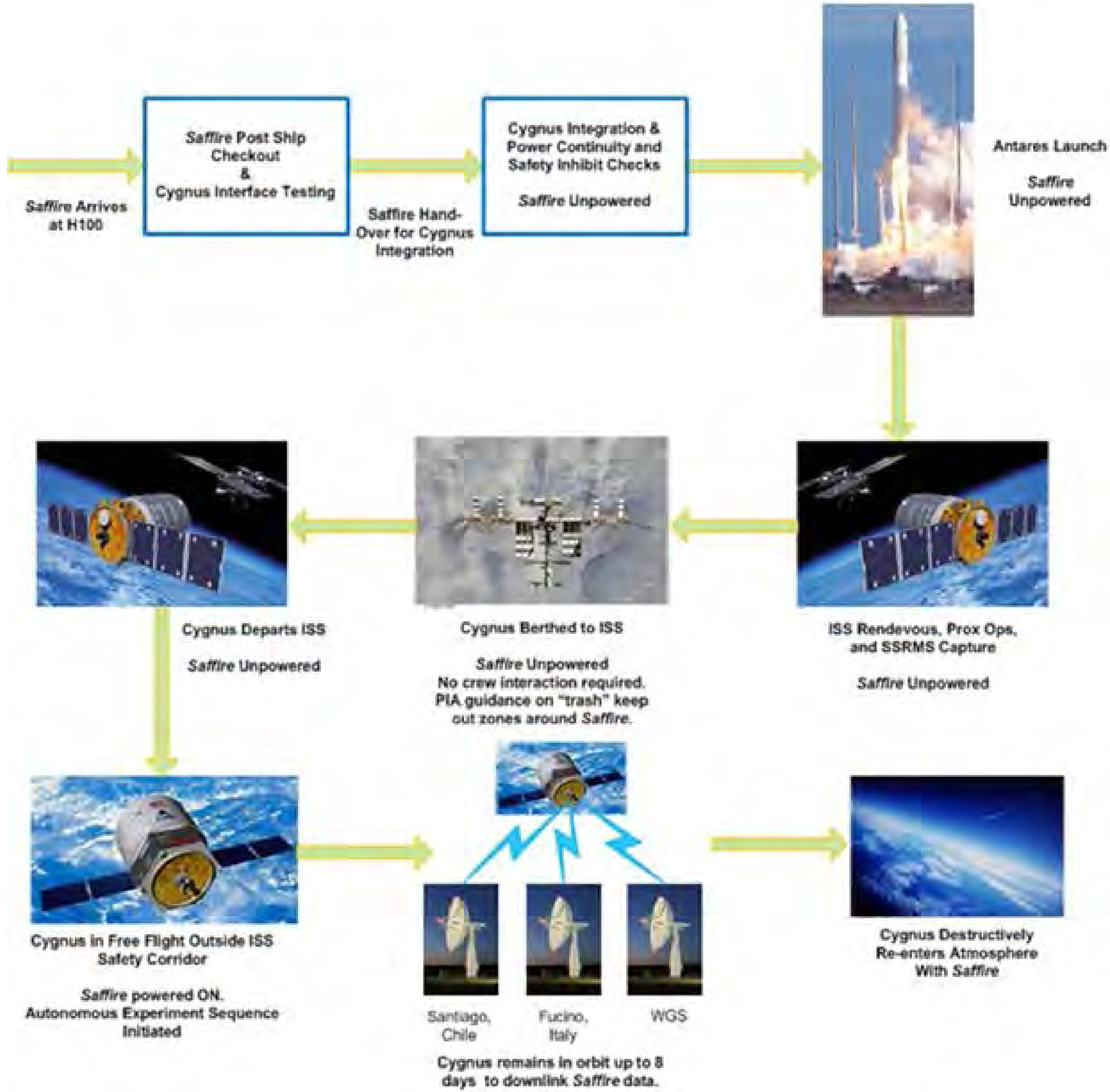


Side view of a low-g flame on a thin paper sample in a convective flow





Operations Concept



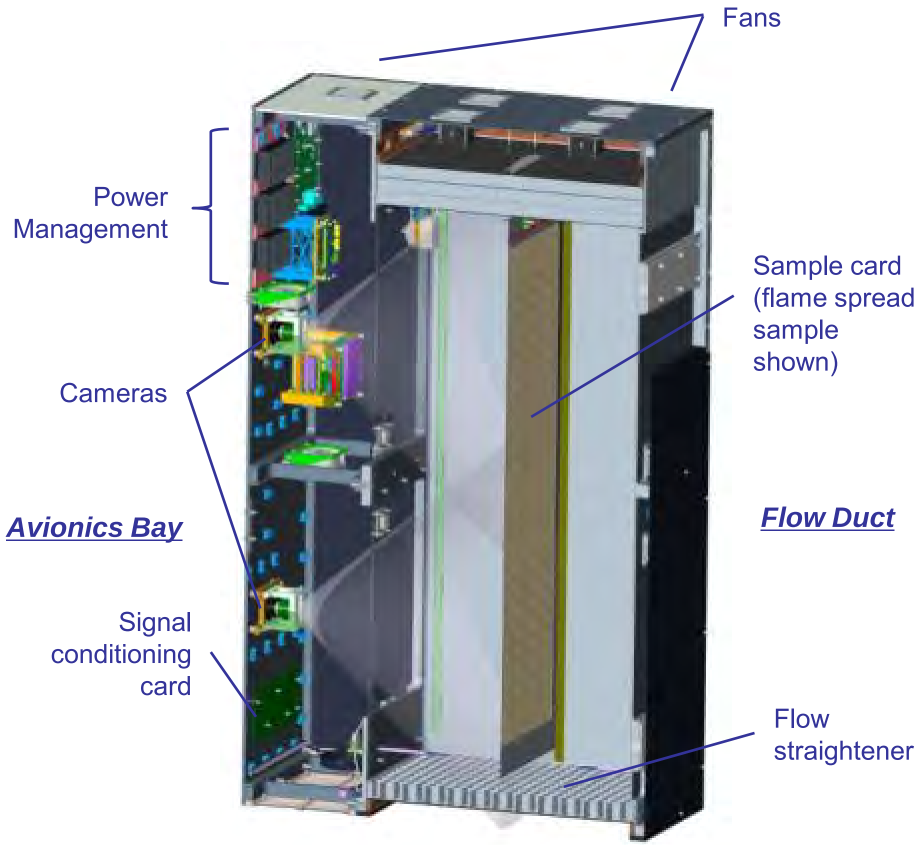
Saffire Overview

Needs:

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

Objectives:

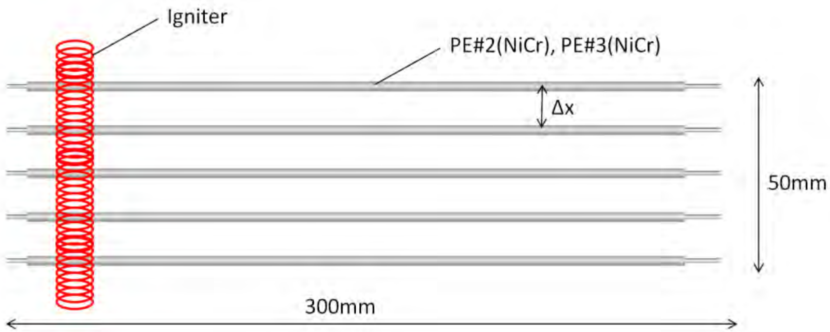
- *Saffire-I*: Assess flame spread of large-scale microgravity fire (spread rate, mass consumption, heat release)
- *Saffire-II*: Verify oxygen flammability limits in low gravity
- *Saffire-III*: Same as Saffire-I at a different flow condition



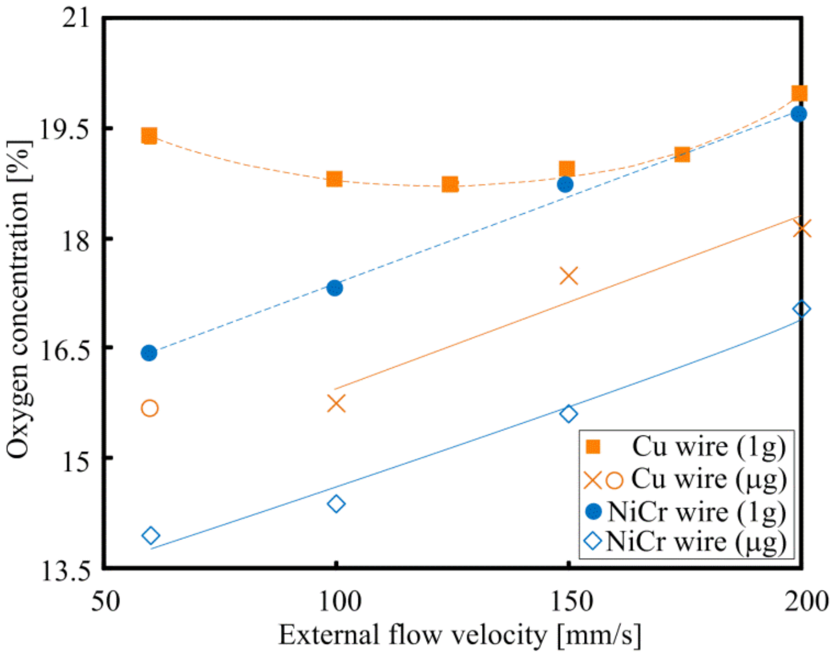
Saffire module consists of a flow duct containing the sample card and an avionics bay. All power, computer, and data acquisition modules are contained in the bay. Dimensions are approximately 53- by 90- by 133-cm

- *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.*

Future Flight – Wire array concept?



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



Limiting oxygen concentration of PE wire with different core material in 1G and 0G. Specification of sample (PE#2): Outer diameter 0.8mm, inner core diameter 0.5mm, insulation thickness 0.15, insulation material is polyethylene .

Cygnus Vehicle Capability

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

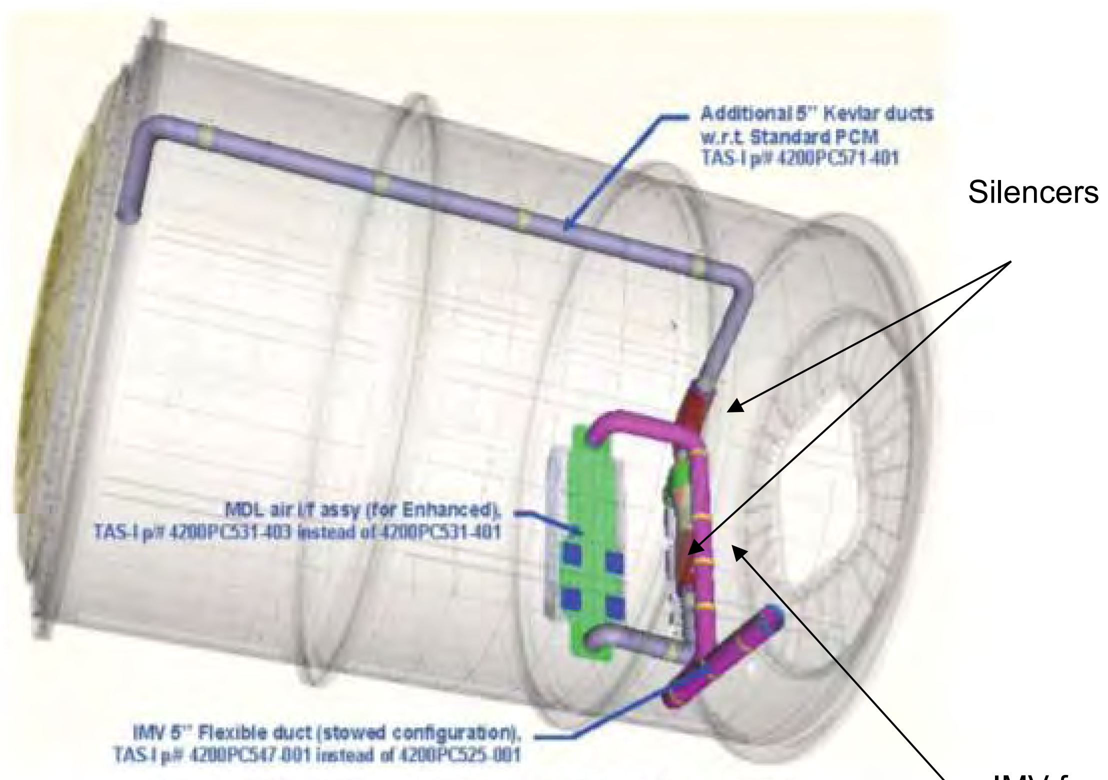


Figure 4.5.2-1 : THC layout (Enhanced PCM – Active Mission)

- Area smoke detector in 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_2 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.**