NASA/TM—2011-217036

Final Report: Fire Prevention, Detection, and Suppression Project

Exploration Technology Development Program

Gary A. Ruff
Glenn Research Center, Cleveland, Ohio

September 2011

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Acknowledgments

The implementation of the Fire Prevention, Detection, and Suppression project described in this report required the dedication and hard work of numerous technologists and project management personnel. Most notably, the researchers in the Microgravity Combustion and Reacting Systems Branch and Instrumentation and Sensors Branch at NASA John H. Glenn Research Center are acknowledged for their contributions to this project and the advancement of fire safety technology for human spaceflight.

Level of Review: This material has been technically reviewed by technical management.

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Abstract

The Fire Prevention, Detection, and Suppression (FPDS) project is a technology development effort within the Exploration Technology Development Program of the Exploration System Missions Directorate (ESMD) that addresses all aspects of fire safety aboard manned exploration systems. The overarching goal for work in the FPDS area is to develop technologies that will ensure crew health and safety on exploration missions by reducing the likelihood of a fire, or, if one does occur, minimizing the risk to the crew, mission, or system. This is accomplished by addressing the areas of (1) fire prevention and material flammability, (2) fire signatures and detection, and (3) fire suppression and response. This report describes the outcomes of this project from the formation of the Exploration Technology Development Program (ETDP) in October 2005 to September 31, 2010 when the Exploration Technology Development Program was replaced by the Enabling Technology Development and Demonstration Program. NASA's fire safety work will continue under this new program and will build upon the accomplishments described herein.

1.0 Project Overview

1.1 Introduction

The Vision for Space Exploration (VSE) announced by President George W. Bush on January 14, 2004 directed NASA to achieve the long-term goal of sending humans back to the Moon and then on to Mars. The amount of knowledge that must be gained and the number of technologies that must be developed before such missions can occur are certainly formidable. The performance standards required for these technologies are, in many cases, well beyond those used on the International Space Station and the Space Shuttle and will stretch our current knowledge of living and working in space. A large number of the challenges are related to ensuring the health and safety of the crew during the exploration mission.

The Exploration Technology Development Program (ETDP) was initiated in 2005 to address the technologies required for the successful completion of the planned exploration missions. This program, led by the Exploration Technology Development Program Office (ETDPO) at NASA Langley Research Center, consisted of 22 projects (at its conclusion) each addressing a required technology development area required by the Constellation Program (CxP). The ETDPO organization chart in Figure 1 shows the projects, lead center, and project manager for each project. Direct oversight, both project management and technical implementation of the Fire Prevention, Detection, and Suppression project was conducted at the NASA Glenn Research Center. This project addressed all aspects of fire safety aboard manned exploration systems.

The overarching goal for work in the FPDS project is to develop technologies that will ensure crew health and safety on exploration missions by reducing the likelihood of a fire, or, if one does occur, minimizing the risk to the crew, mission, or system. This is accomplished by addressing the areas of (1) fire prevention and material flammability, (2) fire signatures and detection, and (3) fire suppression and response. Deliverables from the tasks conducted within the FPDS project could be hardware, design requirements, data for trade studies, test procedures, data libraries, or recommendations for fire response procedures, depending on the area. To realize these deliverables, the project drew on expertise in the disciplines of combustion science, fire safety engineering, risk assessment, failure analysis and systems engineering. The tasks to be conducted take place in normal-gravity test facilities and ground-based microgravity facilities. The successful implementation of this project also depended on results obtained from several experiments to be conducted on the ISS, specifically, the Smoke Aerosol Measurement Experiment (SAME) and the Flame Extinguishment Experiment (FLEX). These projects are being conducted under the ISS Research Project but, while conducted through a different ETDP project, FPDS personnel were responsible for the interpretation and infusion of the data from these experiments into their appropriate technological area in spacecraft fire safety.

1.2 Objectives

The objective of the Fire Prevention, Detection, and Suppression (FPDS) technology development area is to develop hardware, design rules and requirements, and procedures in the three distinct topical areas within FPDS. These include the general areas of (1) Fire Prevention and Material Flammability, (2) Fire Signatures and Detection, and (3) Fire Suppression and Response. Each of these areas has products that will be delivered to exploration systems to ensure crew health and safety. The specific objectives of the tasks in each of these areas are described in the following sections.

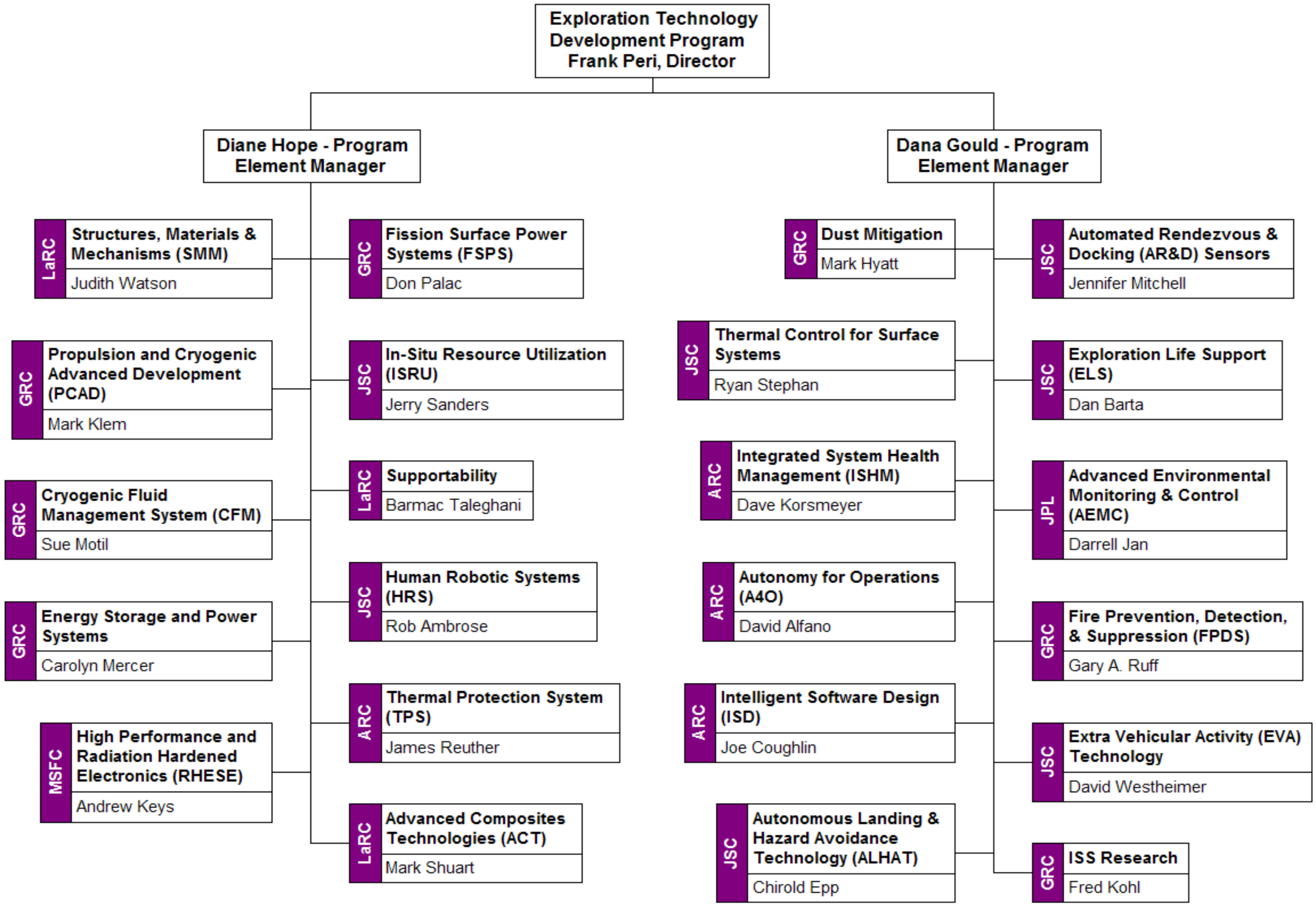


Figure 1.—Projects, Project Managers, and Organization of the Exploration Technology Development Program (ETDP).

1.2.1 Fire Prevention and Material Flammability—Low-g Oxygen Thresholds

The screening of materials to be used on spacecraft to determine their flammability is an integral part of NASA's fire protection strategy. With CxP, NASA took a new approach for the selection of materials in that they are determining the oxygen threshold for a set of important spacecraft materials, identified by NASA Materials and Processes (M&P) personnel, based on standard 1-g flammability tests. However, the oxygen threshold has been shown to be lower in reduced-gravity and is a function of the local convective velocity. *Therefore, the objective of this task was to determine the oxygen flammability threshold in reduced-gravity for materials identified by NASA Materials and Processes personnel and quantify the difference from thresholds determined in normal gravity.*

1.2.2 Fire Signatures and Detection

Constellation vehicles and habitats will require assured fire detection throughout their operational lifetimes. Developments in sensor technology have increased the reliability of fire detection not only by increasing sensor lifetime but decreasing the mass, volume, and power and the rate of nuisance alarms. However, advanced sensors require knowledge of the fire signatures, i.e., the gaseous species and particulate properties produced by a fire that provide the quickest and most reliable detection. Assured fire detection also depends on knowledge of where a fire detector should located and the associated time to detection. (In spacecraft, unlike in terrestrial applications, fire detection is not achieved simply placing a detector on the ceiling and letting the smoke rise!) *The objective of this task was to conduct normal-gravity testing to identify suitable fire signatures, test prototype fire detectors in this normal gravity facility, and model smoke and gaseous contaminant transport in a low-g forced convective environment.*

1.2.3 Fire Detector Development and Testing

Accompanying the task to determine relevant signatures from spacecraft materials and the modeling of smoke transport is the task to develop sensors for fire detection and conduct relevant tests to characterize and verify the performance of the advanced fire detection system. This data is required to conduct trade studies for every CxP vehicle and habitat that will be developed. These trade studies are needed to select a fire detection strategy and appropriate technology that is compatible with the other requirements of the environmental control and life support system. *Within the FPDS project, the objective of this task is to develop and perform tests of candidate particulate and gaseous sensors, improving their performance with each design and test interation. When appropriate, we will also incorporate them into fire detector suite and conduct tests at GRC, JSC, or WSTF to evaluate the fire detection and post-fire monitoring characteristics.* A correlated objective of this portion of the FPDS project is to collect and evaluate data from any candidate fire detection or post-fire monitoring system so that a reliable comparison of their performance is available to perform these trades.

1.2.4 Fire Suppression

As work on the Constellation Program progressed and the designs for the Orion and Altair vehicles matured, contractor and NASA project teams completed independent trade studies of candidate fire suppression systems. Similar to the trade study completed by FPDS personnel in October 2007, they concluded that there was insufficient information to conduct a quantitative trade study of existing fire suppression systems for spacecraft. FPDS personnel developed a plan to obtain this data. Since then fine water mist has become a prime candidate for the portable fire extinguisher on Orion and Altair even though the technology is still being developed. *The objective of this task is to continue to implement the fire suppression test plan to provide data on candidate fire suppression techniques, focusing on water mist fire suppression*.

1.2.5 Post-Fire Monitoring and Response

Fire suppression is intimately linked to post-fire response because not only must the crew clean-up the cabin atmosphere from any smoke or gaseous combustion products, they must also clean-up any fire suppression agent that was discharged. They must do so while probably wearing breathing apparatus or filtering respirators which must be sized to provide protection for the duration of the clean-up process. The connectivity between these procedures and systems requires an integrated approach that includes crew response to the fire alarm, fire suppression, clean-up, and monitoring of the event. The FPDS project has been involved with researchers and engineers from NASA JSC and WSTF to develop a test for the rational evaluation of post-fire monitoring and clean-up equipment and instrumentation. *The objective of this task is to support the development of the post-fire test and of suitable clean-up procedures and monitoring instruments. FPDS technologists will also continue to support the testing and evaluation of instruments for post-fire monitoring that were previously developed from FPDS technologies and are candidates for post-fire monitoring on CxP vehicles*

2.0 Summary of the Technical Accomplishments

During the implementation of the FPDS project, the primary mechanism to document technical results was through the publication of technical papers in conference proceedings and archival journals. Many of these documents are listed in the bibliography. However, the project also documented programmatic plans and overviewed the technical results through numerous presentations to ETDPO as well as to GRC management and other organizations. In July 2010, a presentation was made to representatives of the ETDPO and personnel from the program that was replacing it, the Enabling Technology Development and Demonstration (ETDD) Program. The purpose of these “transition face-to-face” presentations was to summarize the accomplishments of each project in ETDP, status each technology being developed in terms of Technology Readiness Level (TRL), review outstanding technical risks, and document lessons learned during the implementation of the project. The presentation delivered by the FPDS Project Manager is shown in this section.

2.1 FPDS Transition Face-to-Face Presentation

This slides shown in this section was delivered at NASA John H. Glenn Research Center on July 21, 2010 to representatives of the ETDP and ETDD program offices.

National Aeronautics and Space Administration

Fire Prevention, Detection, and Suppression

Face-to-Face Transition Meeting

Gary A. Ruff
NASA John H. Glenn Research Center
Cleveland, OH

July 21, 2010

Background

- Prior to 2001, NASA's emphasis on *technology development* for spacecraft fire safety was through:
  - Justifications for science-based ground-based and flight projects funded by NRA's and the Microgravity Combustion Science Program
  - International collaborations
  - Various groups within NASA
- In 2001, NASA initiated the Bioastronautics Initiative provided funds to allow researchers in the Microgravity Combustion Science Program to transition from basic research to applied fire safety investigations
  - Through the peer-reviewed NASA Research Announcement (NRA) process
- Announcement of the VSE continued the transition towards a technology development projects with a stand-alone fire safety technology development project being formed shortly thereafter
  - Fire Prevention, Detection, and Suppression (FPDS) project within the Exploration Technology Development Program (ETDP)

Outline

- Overview
- FPDS Organization
- Requirements from CxP
- Technology Prioritization Process
- Key Performance Parameters
  - Where we started
  - Where we ended
- Disposition of Risks
- Accomplishments
  - Assessment of TRL for each task
- Remaining tasks and close-out plans
- Lessons Learned

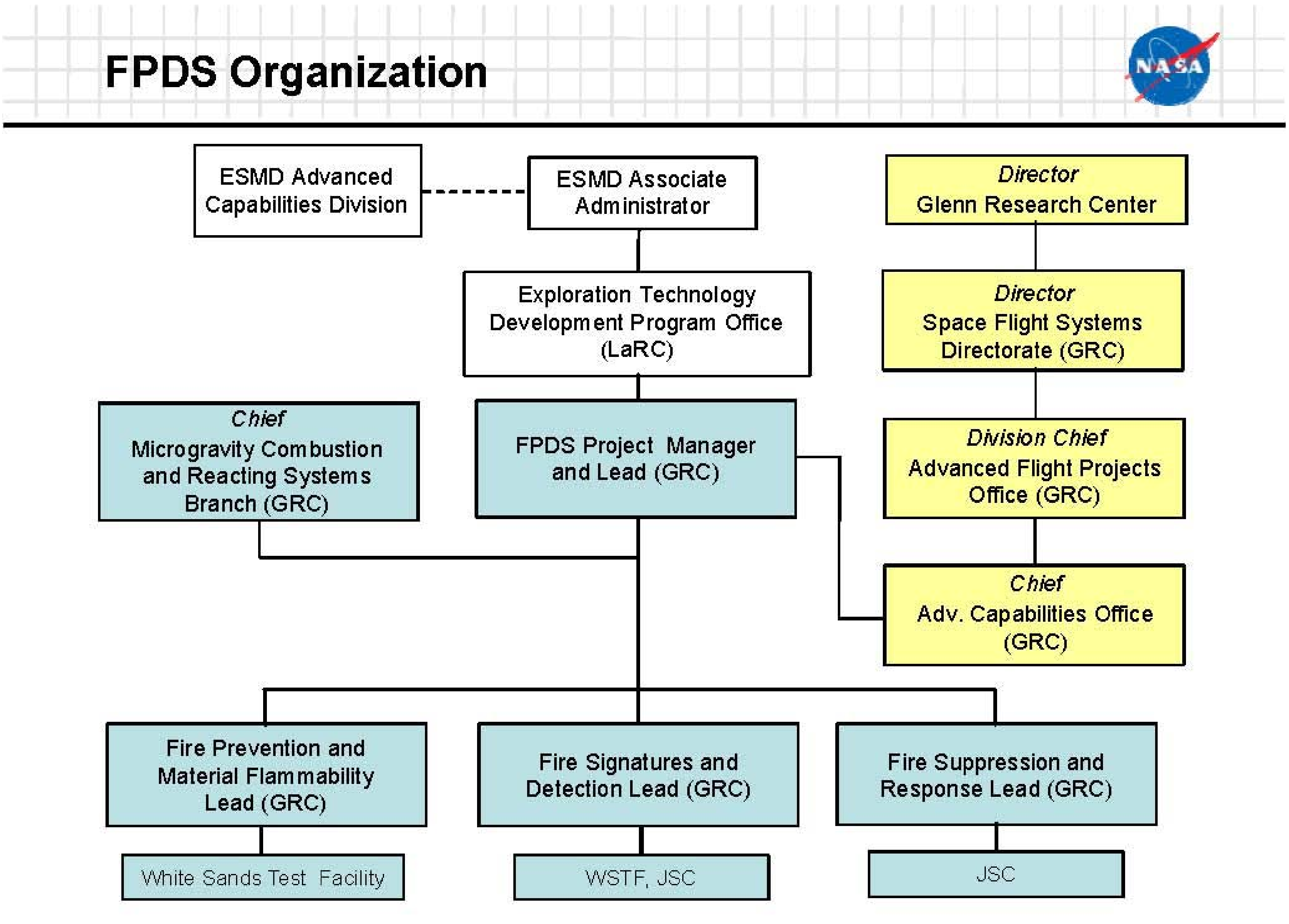
FPDS Overview

- The overarching goal for the FPDS project is to develop technologies that will ensure crew health and safety on exploration missions by reducing the likelihood of a fire, or, if one does occur, minimizing the risk to the crew, mission, or system.
- Accomplished by addressing the areas of:
  1) fire prevention and material flammability
  2) fire signatures and detection,
  3) fire suppression, and
  4) post-fire response
- The Fire Prevention, Detection, and Suppression project is NASA's primary activity for the development of spacecraft fire safety technology
  – *This is an on-going project (and process) that advances fire safety knowledge and technologies in distinct phases*
- During operation of any spacecraft, fire safety issues continuously arise
  – Validity of material flammability testing at off-nominal conditions
  – Analysis of false (nuisance) alarms on fire detection strategy
  – Other combustion-related events

FPDS Overview

- When vehicles are not being developed, we pursue *lower TRL activities*
  - – Understanding ignition, flame spread, and fire suppression in low-g
  - – Development of new flammability test methods
  - – Advancement of sensor technology
- During times of vehicle development, *higher TRL work is emphasized*
  - – Definition of operational atmospheres (material flammability)
  - – Fire suppression strategies and equipment
  - – Post-fire response
    - Development of technologies and relevant testing environments
- Time frame for the delivery of fire safety product spans from 1-2 years before System Requirements Review to Critical Design Review
  - – In many respects, we were late on technology development when CxP was initiated.

➢ The implementation of this project as a technology supplier to the Constellation Program has allowed us to formulate a technology development process for spacecraft fire safety.



FPDS Organization
ESMD Advanced Capabilities Division
ESMD Associate Administrator
Director Glenn Research Center
Exploration Technology Development Program Office (LaRC)
Director Space Flight Systems Directorate (GRC)
Chief Microgravity Combustion and Reacting Systems Branch (GRC)
FPDS Project Manager and Lead (GRC)
Division Chief Advanced Flight Projects Office (GRC)
Chief Adv. Capabilities Office (GRC)
Fire Prevention and Material Flammability Lead (GRC)
Fire Signatures and Detection Lead (GRC)
Fire Suppression and Response Lead (GRC)
White Sands Test Facility
WSTF, JSC
JSC

Constellation requirements driving fire safety

- *Documents*
  - Constellation Architecture Requirements Document (CxP-70000, Revision C, Change 001, March 5, 2009)
  - Human-System Integration Requirements (CxP-70024, Revision C, Change 001, March 6, 2009)
- *What they say*
  - Need a fire detection and suppression system
  - Specify pressure and %O_2 combinations permitted in the habitable volume,
  - Identify the gaseous combustion products that are to be monitored
  - Clean-up after a fire and return the cabin to a habitable condition.
- *What they don't say*
  - Details of the fire detection and suppression systems
    - Required response time
    - Smoke/gas concentrations to detect
    - Clean-up requirements of limitations
    - Fire suppressant type and characteristics
    - Type or size of design fire
  - *Uniformity of fire response equipment across CxP vehicles*
    - Differences in oxygen concentrations, ambient pressures, gravity levels, and consumables in different mission phases

Customer Needs - FY08 TPP

Customer	Criticality	TPP #: Technology	TPP Rank
Orion	Highly Desirable	125: Fire Detection	24
Altair	Highly Desirable	478: Fire Detection	38
Lunar Surf Sys	Highly Desirable	707 & 481: Fire Detection	43
Lunar Surf Sys	Highly Desirable	688: Partial Gravity Fire Suppression	22
Lunar Surf Sys	Highly Desirable	705: Low-g Material Flammability Test	42
Altair	Critical	102: Post-fire Cleanup Monitor	43
Lunar Surf Sys	Critical	630 & 474: Post-fire Cleanup Monitor	39
Lunar Surf Sys	Desirable	716: Low Flammability, Low Toxicity Multicolor Textiles	N/A
Orion	N/A	Low-g Material Flammability Oxygen Thresholds	N/A

- Fire detection is highly desirable for Orion, Altair, and LSS
- Fire suppression only ranked by LSS but Orion has an active tech development program
- Post-fire clean-up monitor was critical for Altair and LSS
  - Orion has an active technology development program
- CxP-wide material flammability issues were not ranked

Key Performance Parameters (FY08)

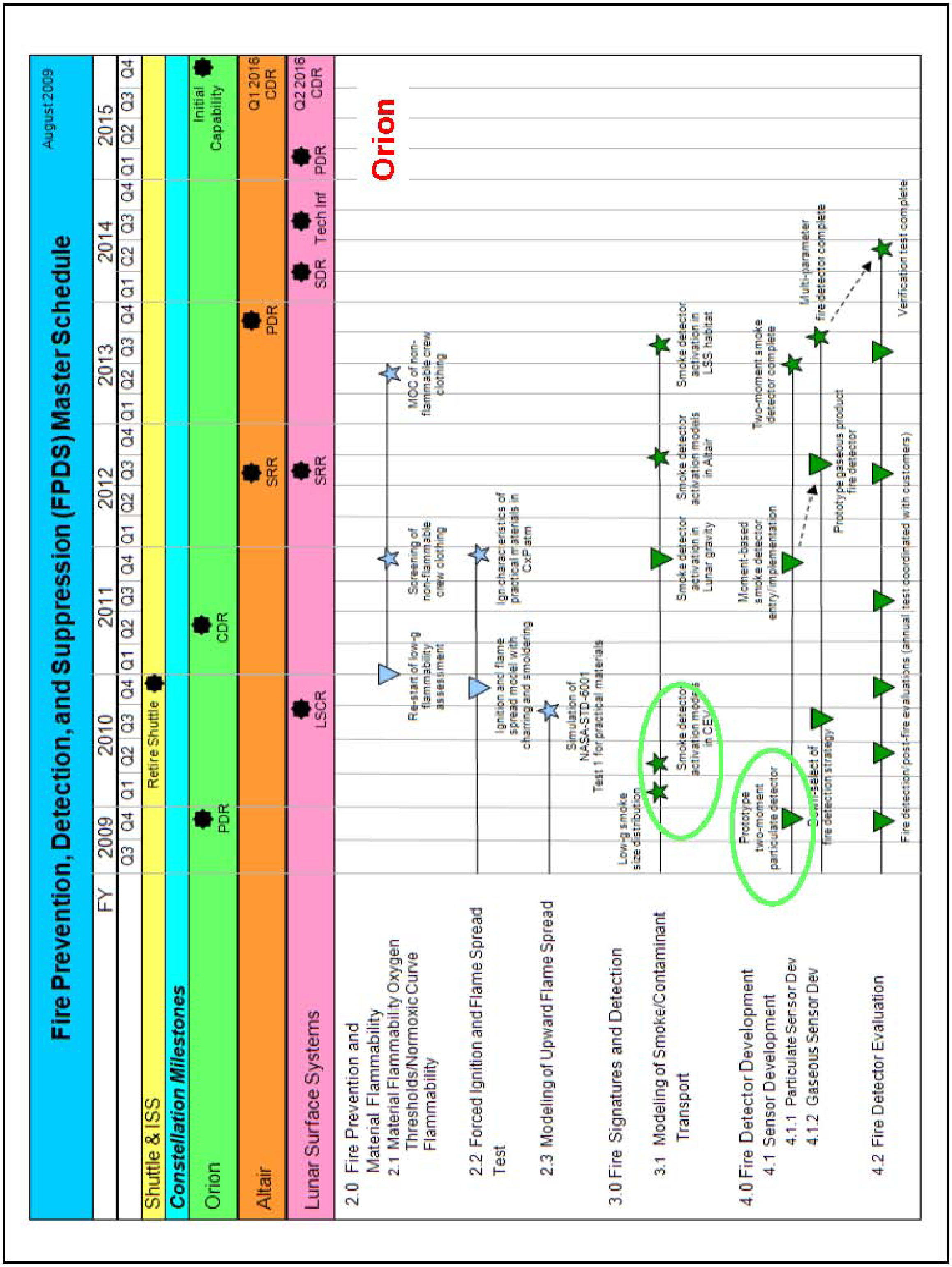
Customer Requirements/Needs	Key Performance Parameters	State-of-the-Art	Performance Target (Full Success)	Performance Target (Minimal Success)	Validation Method
Develop normal gravity test method to evaluate reduced gravity material flammability	Characterization of low-g flammability	Screen materials using 1-g test; apply barriers as directed by M&P	Test(s) to fully describe low-g flammability characteristics and eliminate use of fire barriers	Test(s) to evaluate a single critical low-g flammability parameter (ignition delay, flame spread rate, heat release rate, etc.)	Normal gravity testing; testing in ground-based low-g facilities
Quantitative evaluation of NASA-STD-6001 Test 1	Risk of fire (both probability and severity)	NASA-STD-6001 Test 1	New NASA flammability test to replace NASA-STD-6001 Test 1 that quantifies risk of fires in low-g	Methods to extract quantitative data from NASA-STD-6001 Test 1 to assess relative risk of fires in low-g	Normal gravity testing; testing in ground-based low-g facilities
Design rules for suppressant system including effectiveness of suppressants, required concentrations, and dispersion methods	Mass of fire suppression system	Current ISS	10% reduction in mass	5% reduction in mass	Testing and trade studies
	Mass of suppressant mass released per event	ISS Portable fire extinguishers	20% reduction in mass of suppressant released	no reduction in mass of suppressant released	Testing and analysis
	Mass of consumables req'd for clean-up/recovery	Current ISS	No additional consumables for fire clean-up/recovery	Consumables required specifically for post-fire clean-up and recovery	Analysis
	Replenishment of suppressant	Not currently available	Suppression system rechargeable to pre-use level	Partially rechargeable fire suppression system	Testing and analysis
Analysis and simulation of spacecraft fire scenarios	Decrease response time to fire	Current ISS training	30% decrease in response time	10% decrease in response time	Analysis and simulation

Flammability and Fire Detection Key Performance Parameters (FY10)

Customer Requirements/Needs	Key Performance Parameters	State-of-the-Art	Performance Target (Full Success)	Performance Target (Minimal Success)	Validation Method
Determine oxygen flammability thresholds in low-gravity for relevant CxP materials	Low-gravity oxygen thresholds (Δ %O_2)	Oxygen flammability thresholds as determined by NASA-STD-6001 Test 1 (normal gravity)	Quantification of the difference in oxygen thresholds to within +/- 1% O_2 by volume for thin materials (expt); extrapolation to thick and "real" materials through modeling	Quantification of difference in oxygen thresholds to within +/-1 %O_2 by volume for thin CxP materials	Experimental verification of oxygen flammability thresholds; modeling of materials
Advanced fire detectors	CO monitoring	CO monitoring not used on ISS or STS for fire detection	sensitivity to 1 ppm	sensitivity to 3 ppm	JSC Toxicology Lab verification of CO sensitivity
	Particulate monitoring	ISS and STS smoke detectors	Responds to particles in the range 0.5 to 4 micron; ignore larger particles (dust)	Responds to particles only in the sub-micron range	Characterization against a standard particle source at GRC and/or NIST
	Sensor lifetime	ISS and STS smoke detectors; ISS CSA-CP	Calibrations stable for at least two cycles of being on continuously for 1 month and idle (unpowered) for 6 months.	Correctable calibrations for at least two cycles of being on continuously for 1 month and idle (unpowered) for 6 months.	Lifetime testing at two locations (Makel Engineering, GRC, or JSC)

Fire Suppression Key Performance Parameters (FY10)

Customer Requirements/ Needs	Key Performance Parameters	State-of-the-Art	Performance Target (Full Success)	Performance Target (Minimal Success)	Validation Method
Spacecraft fire suppression	Compatible with ECLSS	Halon incompatible with ISS TCCS	No adverse impact on ECLSS	None	Design and testing
	Low conductivity	Russian foam extinguishers are not to be used on US modules of ISS	Non-conductive	Less than 3960 microseimens (Russian foam extinguisher)	Testing at GRC/JSC
	Clean-up	STS: terminate mission; ISS-Russian: wipe equipment; ISS-US CO removal	No impact to crew or mission after clean-up	Recovery of critical systems	Testing at GRC; analysis
	Rechargeable (LSS only)	Extinguishers are not rechargeable	Recharge extinguishers from existing stores	None	Design and testing
	Fxtinguishing effectiveness	No test fire exists (1-g or 0-g)	Extinguish two test fires with 30 sec of discharge	Fxtinguish test fire with 30 sec discharge	Testing at GRC or WSTF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4.1 Sensor Development
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4.1.2 Gaseous Sensor Dev
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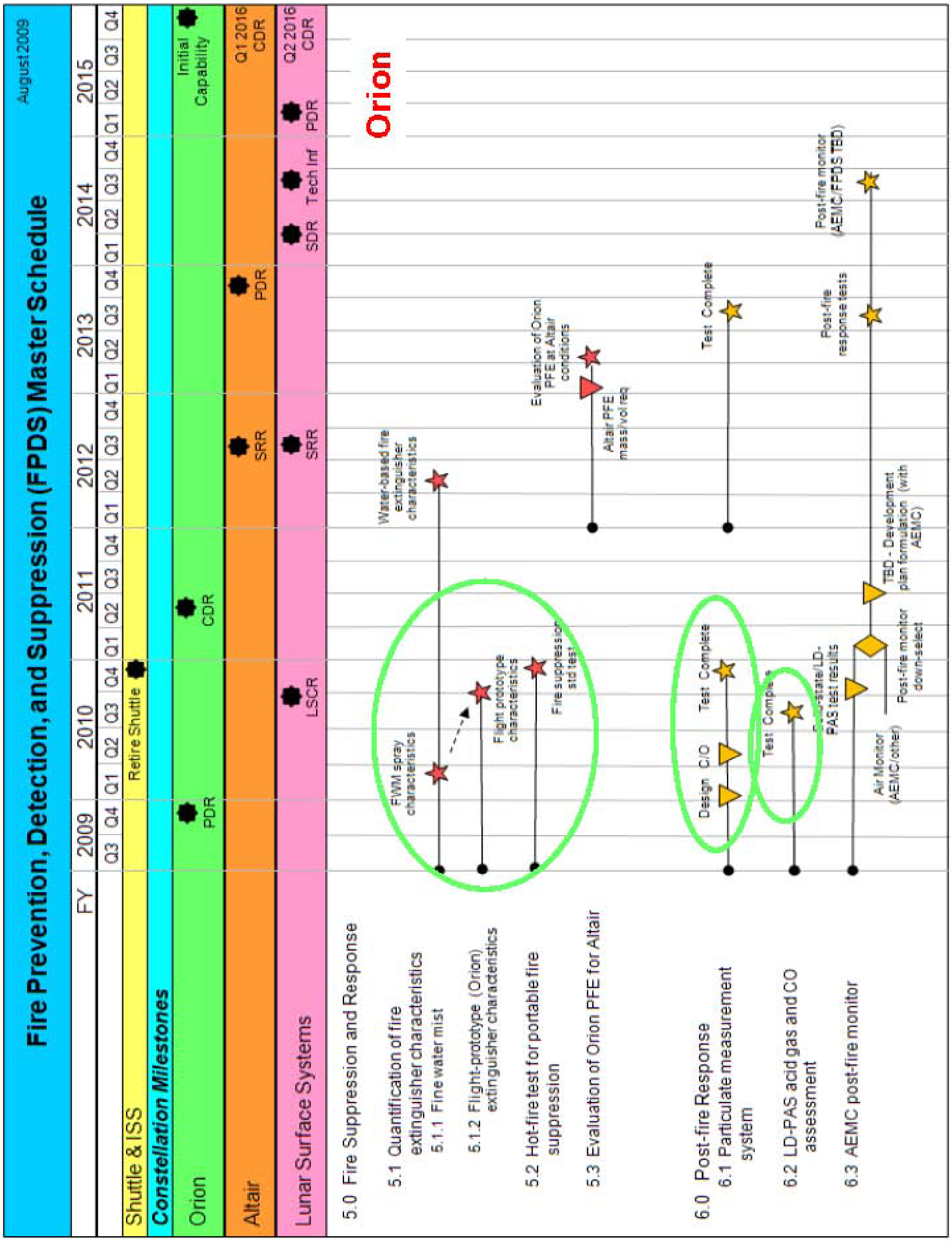
MOC of non-flammable crew clothing
Ignition and flame spread model with charring and smoldering
Ign characteristics of practical materials in CxP atm
Simulation of NASA-STD-6001 Test 1 for practical materials
Low-g smoke size distribution
Smoke detector activation models in CEV
Smoke detector activation in Lunar gravity
Smoke detector activation models in Altair
Smoke detector activation in LSS habitat
Prototype two-moment particulate detector
Down-select of fire detection strategy
Moment-based smoke detector entry/implementation
Prototype gaseous product fire detector
Two-moment smoke detector complete
Multi-parameter fire detector complete
Fire detection/post-fire evaluations (annual test coordinated with customers)
Verification test complete



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5.2 Hot-fire test for portable fire suppression
5.3 Evaluation of Orion PFE for Altair
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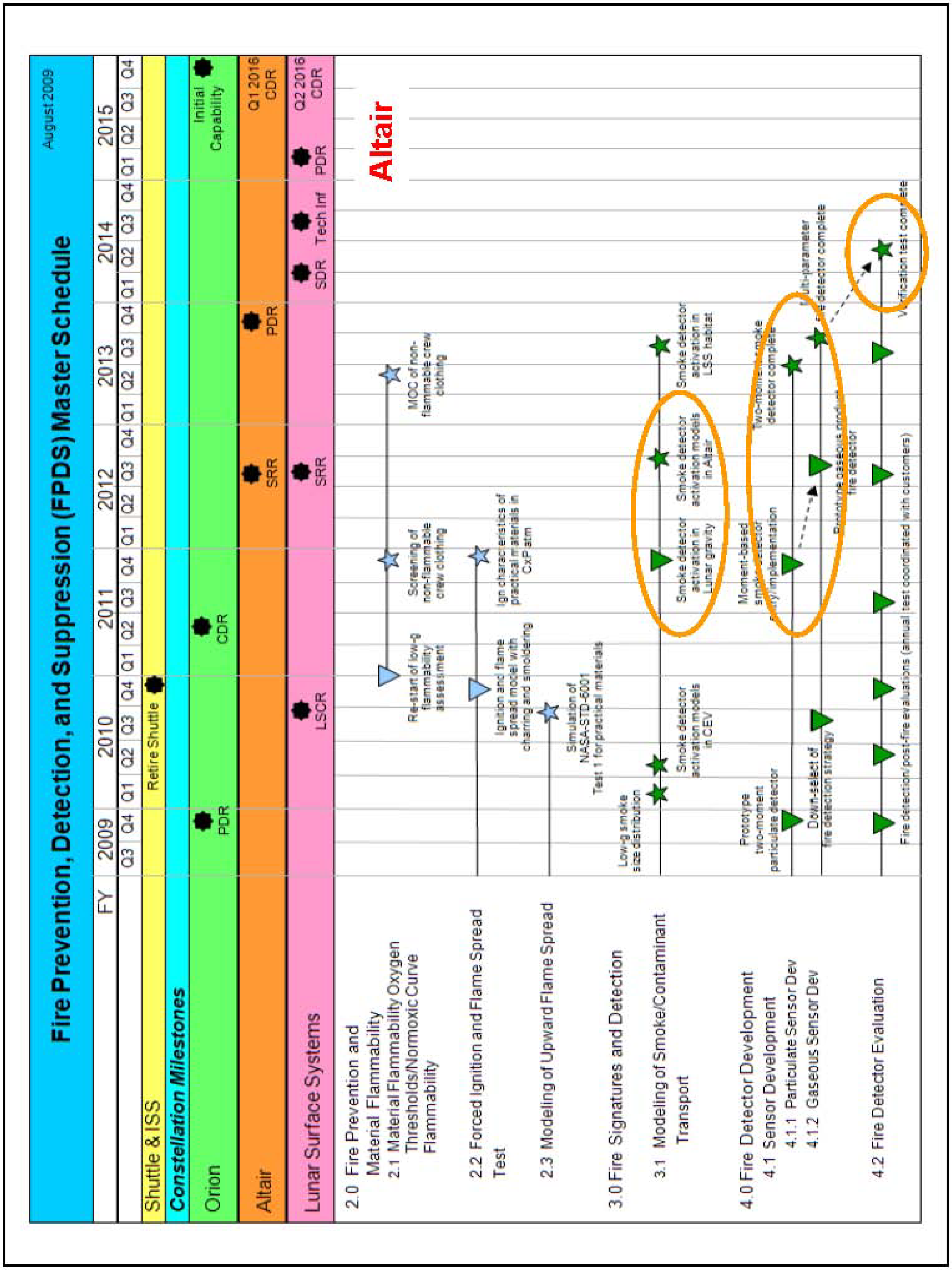
6.3 AEMC post-fire monitor
FWM spray characteristics
Flight prototype characteristics
Fire suppression std test
Water-based fire extinguisher characteristics
Altair PFE mass/vol req
Evaluation of Orion PFE at Altair conditions
Design
C/O
Test Complete
Test Complete
Air Monitor (AEMC/other)
Post-fire monitor down-select
TBD - Development plan formulation (with AEMC)
Post-fire response tests
Post-fire monitor (AEMC/FPDS TBD)



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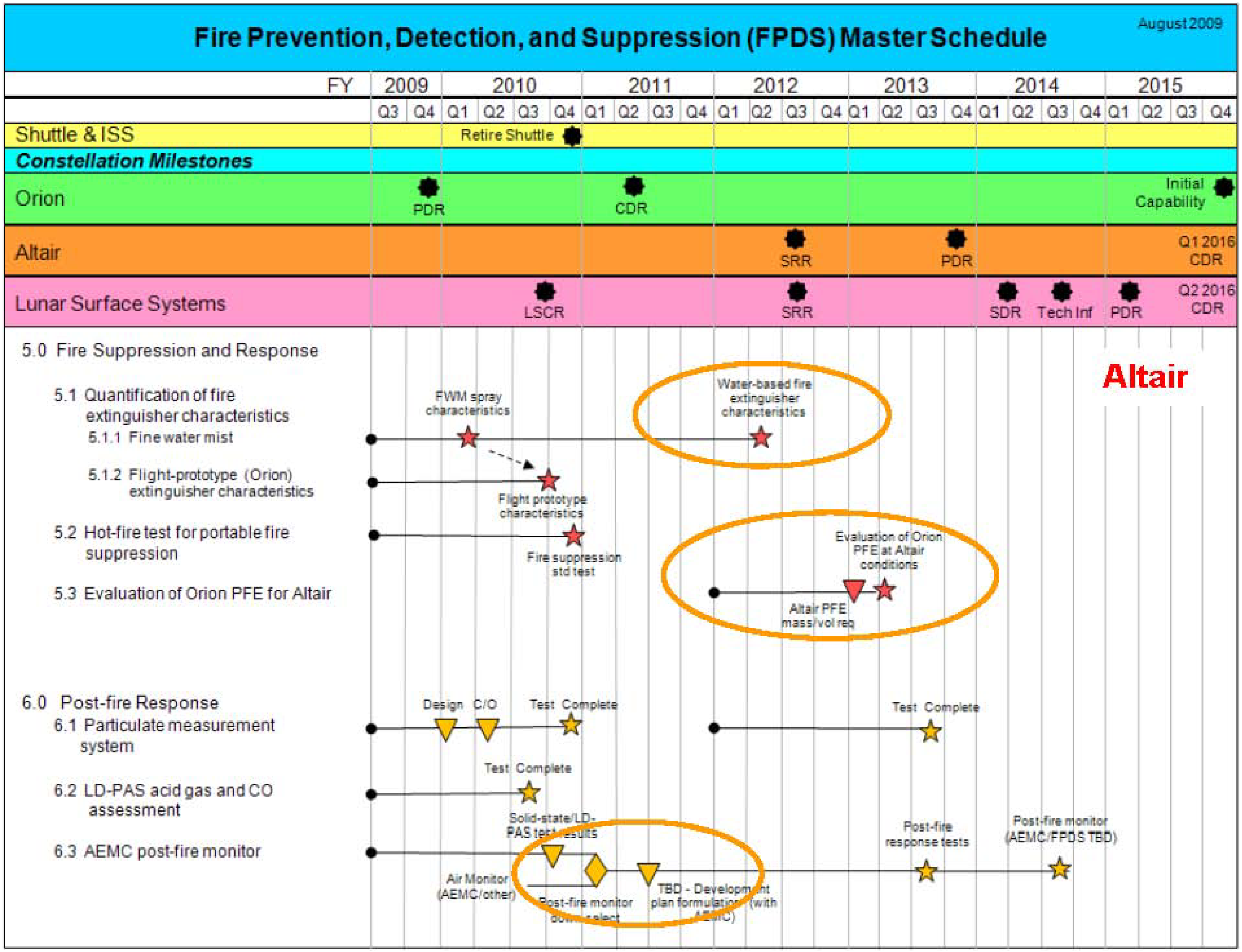
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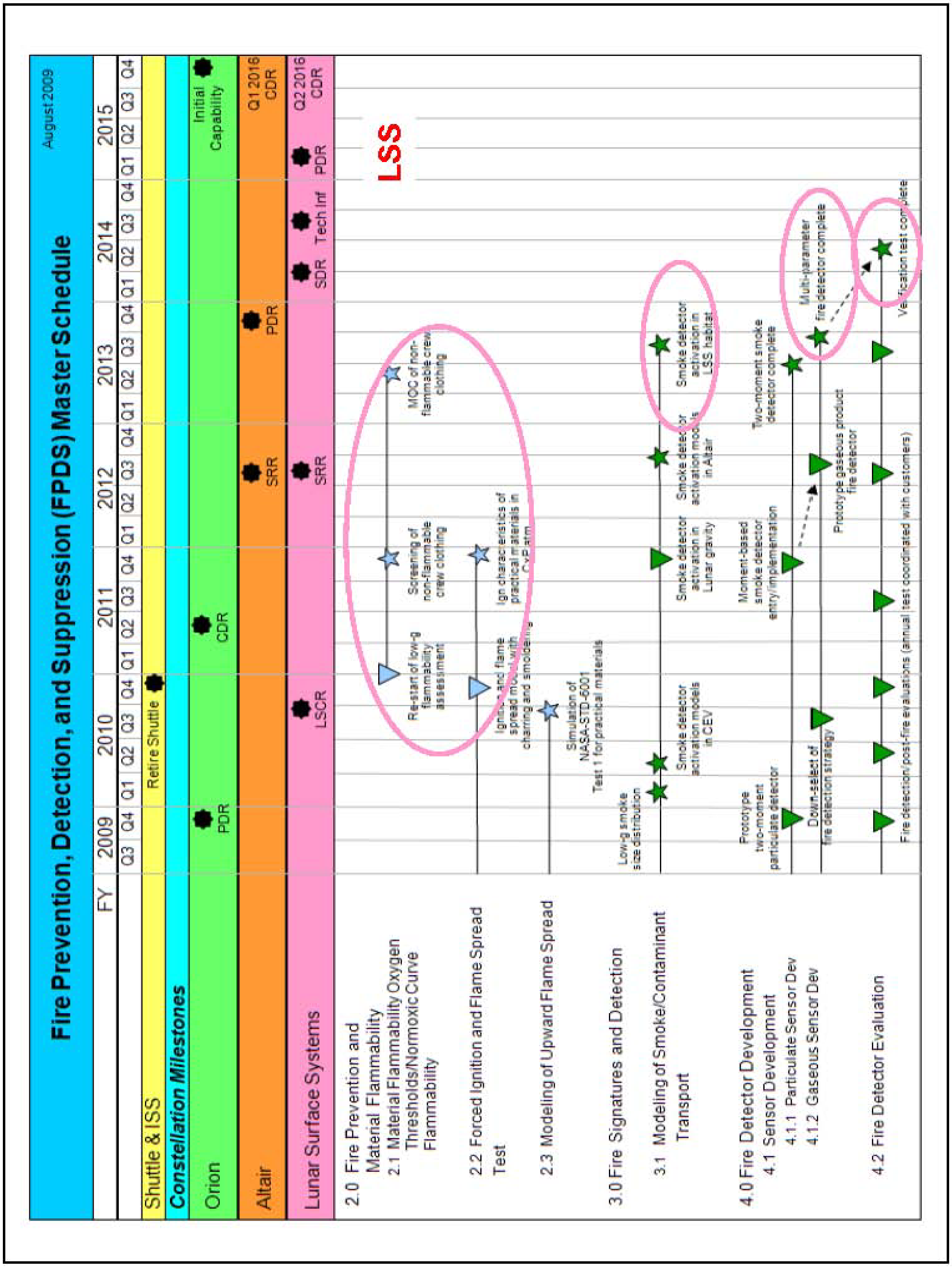
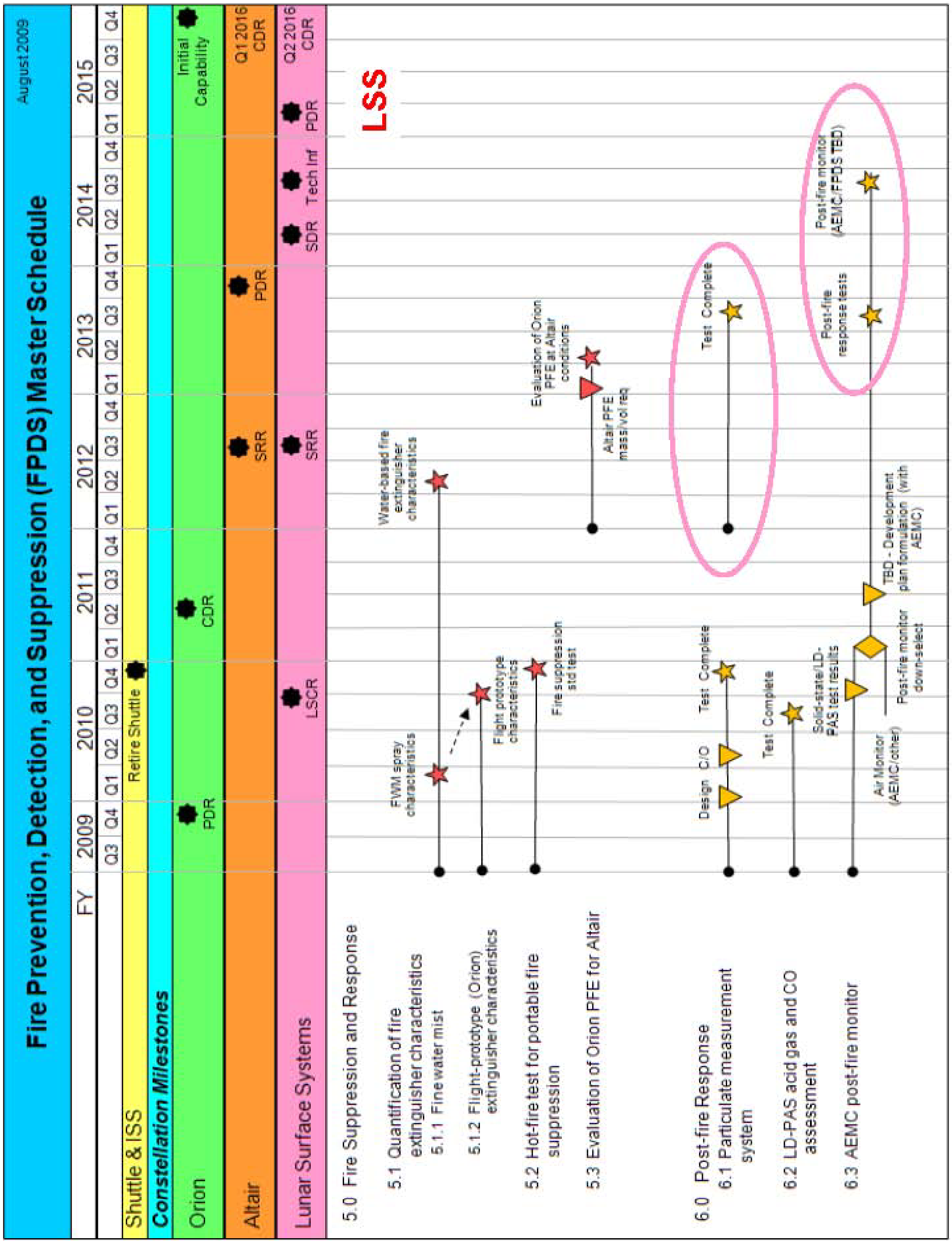
6.0 Post-fire Response
6.1 Particulate measurement system
6.2 LD-PAS acid gas and CO assessment
6.3 AEMC post-fire monitor
Design
C/O
Test Complete
Test Complete
Test Complete
Solid-state/LD-
Air Monitor (AEMC/other)
Post-fire monitor
TBD - Developm
Post-fire response tests
Post-fire monitor (AEMC/FPDS TBD)


Fire Prevention, Detection, and Suppression (FPDS) Master Schedule
August 2009
FY
2009
2010
2011
2012
2013
2014
2015
Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4
Shuttle & ISS
Retire Shuttle
Constellation Milestones
Orion
PDR
CDR
Initial Capability
Altair
SRR
PDR
Q1 2016 CDR
Lunar Surface Systems
LSCR
SRR
SDR
Tech Inf
PDR
Q2 2016 CDR
LSS
2.0 Fire Prevention and Material Flammability
2.1 Material Flammability Oxygen Thresholds/Normoxic Curve Flammability
2.2 Forced Ignition and Flame Spread Test
2.3 Modeling of Upward Flame Spread
3.0 Fire Signatures and Detection
3.1 Modeling of Smoke/Contaminant Transport
4.0 Fire Detector Development
4.1 Sensor Development
4.1.1 Particulate Sensor Dev
4.1.2 Gaseous Sensor Dev
4.2 Fire Detector Evaluation
Re-start of low-g flammability assessment
Screening of non-flammable crew clothing
MOC of non-flammable crew clothing
Ignition and flame spread model with charring and smoldering
Ign characteristics of practical materials in CxP atm
Simulation of NASA-STD-6001 Test 1 for practical materials
Low-g smoke size distribution
Smoke detector activation models in CEV
Smoke detector activation in Lunar gravity
Smoke detector activation models in Altair
Smoke detector activation in LSS habitat
Prototype two-moment particulate detector
Moment-based smoke detector entry/implementation
Two-moment smoke detector complete
Down-select of fire detection strategy
Prototype gaseous product fire detector
Multi-parameter fire detector complete
Fire detection/post-fire evaluations (annual test coordinated with customers)
Verification test complete



Fire Prevention, Detection, and Suppression (FPDS) Master Schedule
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5.0 Fire Suppression and Response
5.1 Quantification of fire extinguisher characteristics
5.1.1 Fine water mist
FWM spray characteristics
Water-based fire extinguisher characteristics
5.1.2 Flight-prototype (Orion) extinguisher characteristics
Flight prototype characteristics
5.2 Hot-fire test for portable fire suppression
Fire suppression std test
5.3 Evaluation of Orion PFE for Altair
Altair PFE mass/vol req
Evaluation of Orion PFE at Altair conditions
6.0 Post-fire Response
6.1 Particulate measurement system
Design
C/O
Test Complete
Test Complete
6.2 LD-PAS acid gas and CO assessment
Test Complete
6.3 AEMC post-fire monitor
Air Monitor (AEMC/other)
Solid-state/LD-PAS test results
Post-fire monitor down-select
TBD - Development plan formulation (with AEMC)
Post-fire response tests
Post-fire monitor (AEMC/FPDS TBD)

FPDS Risks

- Risks as of October FY09

Trend	Risk ID and Open Date	Risk Title	Risk Statement (MUST USE - "Given that..there is a possibility..)	L	C	Affinity Group (Budget, Performance, Cost, Schedule)	Owner/ Initiator	Approach (M,W,A,R)	Status/ Context	Mitigation 1	Estimated Start Date Mitigation 1	Estimated End Date Mitigation 1
⇨	F1 (10/1/2008)	Low-g Flammability Task Termination	Given the current FY10 PPBE in-guide submits, there is a possibility that we will be unable to supply sufficient low-g oxygen threshold data to CxP M&P to incorporate low-g safety margins into the FDS strategy for Orion/Altair.	4	3	Performance	GAR	W, M	The difference between the maximum oxygen concentration and the atmospheric %O_2 determines whether fire detection and suppression are required.	This work remains out of scope for FY09. We conducted lunar-g MOC tests using LSS funding and will conduct tests as other funding sources become available. We will coninue to interact with customers on issues of low-g material flammability and advocate for future funding as necessary	1-Oct-08	
⇨	F2 (10/1/2008)	Loss of Key Personnel - Drop Tower	Given that there is no FY09 funding for material flammability, there is a possibility that key personnel will be lost to other projects.	4	3	Performance, Cost	GAR	M	There is unique experience required for the operation of low-gravity test facilities and analysis of the data. Re-training personnel will become increasingly difficult as the experience base erodes.	Drop tower techs are currently being re-assigned to other facilities as the use of the Zero-Gravity Facility has significantly decreased. Occasional tests have been conducted using non-FPDS funds and have maintained capability and workforce (9/15/09)	1-Oct-08	30-Sep-10
⇨	D1 (10/1/2008)	Acid Gas Fire Detection	Given that the detection of acid gases, such as HF or HCl, is not a standard fire detection method, there is a possibility that the approach will not prove suitable for spacecraft fire detection.	4	3	Performance	GAR	M	The detection of acid gases such as HF or HCl is required for post-fire monitoring. Verification of these species for fire detection could allow the same instrument to be used for both fire detection and monitoring.	We will mitigate this risk by conducting tests to evaluate the production of these gases in the early phases and during a typical spacecraft fire. Also, we will pursue the development of CO and particulate sensors that are more established for fire detection.	1-Aug-08	30-Sep-09
⇩	D2 (10/1/2008)	Low-concentration CO Detection	Given that the FY08 low-concentration CO sensor demonstrated increased noise in a practical pre-fire environment, there is a possibility that these sensors will prove not to be viable.	3	4	Performance	GAR	W, M	The levels of CO required for post-fire monitoring are substantially less than those required for fire detection. One sensor that could span both regimes would satisfy both applications.	Continued development of sensors has continued to improve performance and another set of tests will be performed in October 2009. Other technologies for monitoring CO have tested well in post-fire applications. (9/15/09)	1-Oct-08	30-Nov-09
⇧	D3 (10/1/2008)	Unavailability of Sensor Testing Opportunities	Given that the FPDS project does not support the post-fire cleanup tests conducted at WSTF (a.k.a. the Smoke Eater Tests), there is a possibility that these tests will not be conducted or conducted at suitable times to satisfy FPDS milestones	4	4	Schedule	GAR	W, M	The Smoke Eater tests have been conducted each of the past two years, generally in the late spring or summer. While the original purpose was to evaluate post-fire air cleanup equipment, they have been useful to demonstrate post-fire monitoring instruments. However, the tests conducted in FY09 did not match FPDS planned development, resulting in no post-fire tests for the FY09 products.	Tests have begun in a new facility at WSTF that is dedicated to the evaluation and monitoring of post-fire clean-up. Because there is a need for more tests by FPDS and the project has insufficient funds to conduct our own tests, we will continue to schedule our tests around other's schedules.	1-Oct-08	
⇨	D4 (1/14/2009)	Loss of Key Personnel - Particulate Monitor	Given that highly skilled technicians are required to manufacture components for the advanced particulate detector and FPDS cannot fully support these personnel, there is a possibility that they will be reassigned and be unavailable to this project	4	3	Schedule, Performance	GAR/PG	W, M	FPDS and several other technology projects at GRC supported several technicians who were very skilled and have become familiar with the requirements of each task. Funding reductions have forced all but one to be relocated and it appears he, too, will be relocated. This will directly impact the particulate sensor development task.	We have requested at least 20% of the technician's time to support our work. However, he will be in another location and it will be more difficult to schedule time. We will continue to watch this issue to assess and predict impacts to the FPDS tasks.	1-Jan-09	
⇨	S1 (10/1/2008)	Fire Suppression Development	Given that there is a desire for common open cabin fire suppressant across the CxP architecture and that insufficient information is available on candidate suppressants to perform suitable trades, there is a possibility that a suppression agent selected for one vehicle may not be suitable for other CxP vehicles.	4	4	Performance, Cost	GAR	M	Fire extinguishers on current space vehicles are generally incompatible with the systems to which they dock or are attached. Using incomplete data on extinguisher performance during trade studies and design increases the likelihood that this trend will continue through CxP.	We will mitigate this risk by conducting tasks to obtain the required data on candidate suppression agents. However, the risk still exists that there will be insufficient funds to completed the planned test program.	1-Aug-08	

FPDS Risks

- Risks as of October FY10

Trend	Risk ID and Open Date	Risk Title/WBS	Risk Statement (MUST USE - "Given that..there is a possibility..)	L	C	Affinity Group (Budget, Performance, Cost, Schedule)	Owner/ Initiator	Approach (M,W,A,R)	Status/ Context	Mitigation 1	Estimated Start Date Mitigation 1	Estimated End Date Mitigation 1
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⇨	F2 (10/1/2008)	Loss of Key Personnel - Drop Tower (344397.04.01.03)	Given that there is no FY10 funding for material flammability, there is a possibility that key personnel will be lost to other projects.	4	3	Performance, Cost	GAR	M	There is unique experience required for the operation of low-gravity test facilities and analysis of the data. Re-training personnel will become increasingly difficult as the experience base erodes.	Drop tower techs are currently being re-assigned to other facilities as the use of the Zero-Gravity Facility has significantly decreased. Occasional tests have been conducted using non-FPDS funds and have maintained capability and workforce (9/15/09)	1-Oct-08	30-Sep-10
⇩	D1 (10/1/2008)	Low-concentration CO Detection	Given that the FY08 low-concentration CO sensor demonstrated increased noise in a practical pre-fire environment, there is a possibility that these sensors will prove not to be viable.	3	4	Performance	GAR	W, M	The levels of CO required for post-fire monitoring are substantially less than those required for fire detection. One sensor that could span both regimes would satisfy both applications.	Continued development of sensors has continued to improve performance and another set of tests will be performed in October 2009. Other technologies for monitoring CO have tested well in post-fire applications. (9/15/09)	1-Oct-08	30-Oct-09
⇧	D2 (10/1/2008)	Unavailability of Sensor Testing Opportunities (344397.04.03.03.01 and 344397.04.03.03.02)	Given that the FPDS project does not fund the post-fire cleanup tests conducted at WSTF (a.k.a. the Smoke Eater Tests), there is a possibility that these tests will not be conducted or conducted at suitable times to satisfy FPDS milestones	4	4	Schedule	GAR	W, M	The Smoke Eater tests have been conducted each of the past two years, generally in the late spring or summer. While the original purpose was to evaluate post-fire air cleanup equipment, they have been useful to demonstrate post-fire monitoring instruments. However, the tests conducted in FY09 did not match FPDS planned development, resulting in no post-fire tests for the FY09 products.	Tests have begun in a new facility at WSTF that is dedicated to the evaluation and monitoring of post-fire clean-up. Because there is a need for more tests by FPDS and the project has insufficient funds to conduct our own tests, we will continue to schedule our tests around other's schedules. BY Sept 2010, we will reassess risks relative to Orion's plans for post-fire reponse.	1-Oct-08	30-Sep-10
⇨	D3 (1/14/2009)	Loss of Key Personnel - Particulate Monitor (344397.04.03.03.02)	Given that highly skilled machinists and technicians are required to manufacture components for the advanced particulate detector and FPDS cannot fully support these personnel, there is a possibility that they will be reassigned and be unavailable to this project	4	3	Schedule, Performance	GAR/PG	W, M	FPDS and several other technology projects at GRC supported several technicians who were highly skilled and very familiar with the requirements of each task. Funding reductions have forced all of them to be relocated. This will directly impact the particulate sensor development task.	We have requested an appropriate number of the technician's time to support our work. However, availability when needed may be remain an issue. We will continue to watch this issue to assess and predict impacts to the FPDS tasks.	1-Jan-09	30-Sep-11
⇨	S1 (10/1/2008)	Fire Suppression Development (344397.04.04.03)	Given that there is a desire for common open cabin fire suppressant across the CxP architecture and that insufficient information is available on candidate suppressants to perform suitable trades, there is a possibility that a suppression agent selected for one vehicle may not be suitable for other CxP vehicles.	4	4	Performance, Cost	GAR	M	Fire extinguishers on current space vehicles are generally incompatible with the systems to which they dock or are attached. Using incomplete data on extinguisher performance during trade studies and design increases the likelihood that this trend will continue through CxP.	We will mitigate this risk by conducting tests to obtain the required data on candidate suppression agents. However, the risk still exists that there will be insufficient funds to completed the planned test program by the time decisions are made.	1-Aug-08	30-Sep-10

FPDS Risks

- Risks as of July 2010

Trend	Risk ID and Open Date	Risk Title/WBS	Risk Statement (MUST USE - "Given that..there is a possibility..)	L	C	Affinity Group (Budget, Performance, Cost, Schedule)	Owner/ Initiator	Approach (M,W,A,R)	Status/ Context	Mitigation 1	Estimated Start Date Mitigation 1	Estimated End Date Mitigation 1
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⇨	D2 (10/1/2008)	Unavailability of Sensor Testing Opportunities (344397.04.03.03.01 and 344397.04.03.03.02)	Given that the FPDS project does not fund the post-fire cleanup tests conducted at WSTF (a.k.a. the Smoke Eater Tests), there is a possibility that these tests will not be conducted or conducted at suitable times to satisfy FPDS milestones	4	4	Schedule	GAR	W, M	The Smoke Eater tests have been conducted each of the past two years, generally in the late spring or summer. While the original purpose was to evaluate post-fire air cleanup equipment, they have been useful to demonstrate post-fire monitoring instruments. However, the tests conducted in FY09 did not match FPDS planned development, resulting in no post-fire tests for the FY09 products.	Tests have begun in a new facility at WSTF that is dedicated to the evaluation and monitoring of post-fire clean-up. Orion is not performing tests so FPDS will be funding our own tests. Plans are made to develop a portion of this capability at GRC so testing can proceed in a more timely manner. (5/12/2010)	1-Oct-08	30-Sep-10
⇨	D3 (1/14/2009)	Loss of Key Personnel - Particulate Monitor (344397.04.03.03.02)	Given that highly skilled machinists and technicians are required to manufacture components for the advanced particulate detector and FPDS cannot fully support these personnel, there is a possibility that they will be reassigned and be unavailable to this project	4	3	Schedule, Performance	GAR/PG	W, M	FPDS and several other technology projects at GRC supported several technicians who were highly skilled and very familiar with the requirements of each task. Funding reductions have forced all of them to be relocated. This will directly impact the particulate sensor development task.	We have requested an appropriate number of the technician's time to support our work. However, availability when needed may be remain an issue. We will continue to watch this issue to assess and predict impacts to the FPDS tasks.	1-Jan-09	30-Sep-11
⇨	D4 (11/30/2009)	Low-concentration CO Detection	Given that the FY08 and FY09 low-concentration CO sensor demonstrated anomalous behavior in a practical pre-fire environment, there is a possibility that the Pt-Rutile-type sensors will prove not to be viable.	3	4	Performance	GAR	W, M	The levels of CO required for post-fire monitoring are substantially less than those required for fire detection. One sensor that could span both regimes would satisfy both applications.	Progress has been made in achieving CO concentrations less than 5 ppm using Pt-Rutile and LC sensors. These solutions will continue to be evaluated. Other technologies are also being developed. (5/12/10)	1-Dec-09	30-Sep-10

- **By end of FY10, testing could remove Risk D4: Low-concentration CO Detector.**
  - Issues could then be calibration
  - Laser spectroscopic technologies are alternatives
- **Other risks could remain relevant but will be re-evaluated in the new program**

FPDS Major Accomplishments

- Low-g Maximum Oxygen Concentration tests
  - *For the first time, quantifies the difference between 0-g, Lunar-g and 1-g MOC for relevant materials*
- Flammability correlations as functions of pressure, velocity, and %O_2
  - *What is the impact on material flammability as you trade oxygen concentration and pressure?*
- Ignitability of materials increases as pressure decreases
- Fire Detection
  - Interpretation of results for the Smoke Aerosol Measurement Experiment (SAME) and SAME-R (Reflight)
  - Development of the Multiparameter Aerosol Scattering Spectrometer
  - Simulation of smoke detector activation
- Water mist fire extinguisher
  - Sufficiently raised TRL for extinguisher to warrant a change in Orion baseline
- Post-fire Clean-up
  - Development of a standard challenge
  - Suite of instrumentation (from SBIRs)

Low-g Oxygen Flammability Threshold Tests

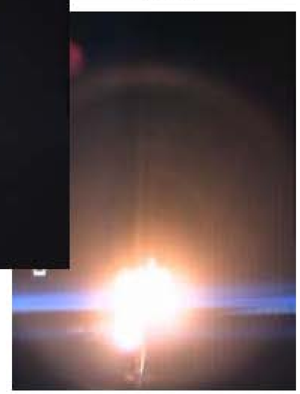
Objective

- Quantify the low-g flammability thresholds for typical spacecraft materials and compare results with thresholds determined in normal gravity

Ultem 1000

Nomex

Mylar

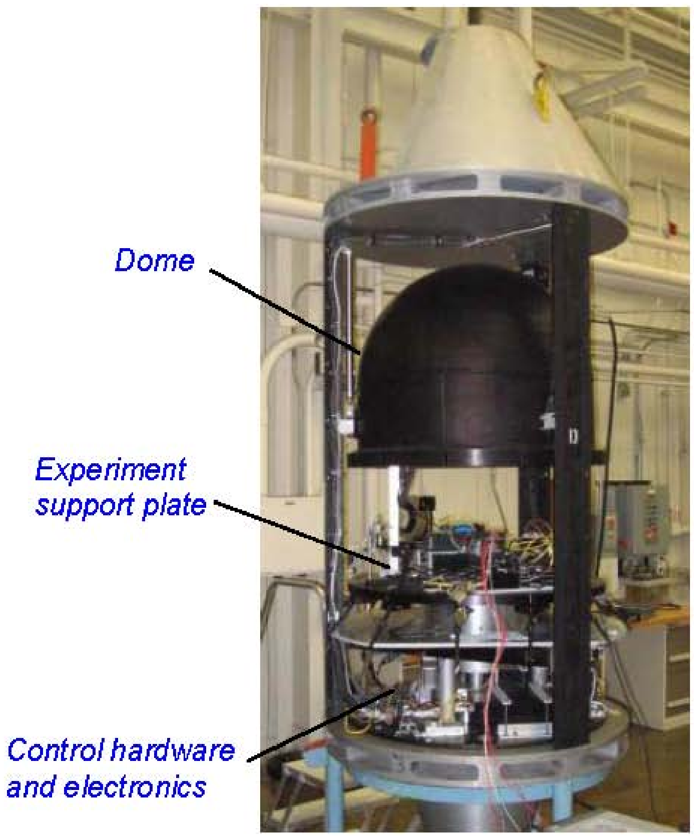


ZGF drop tower rig with Combustion Tunnel facility

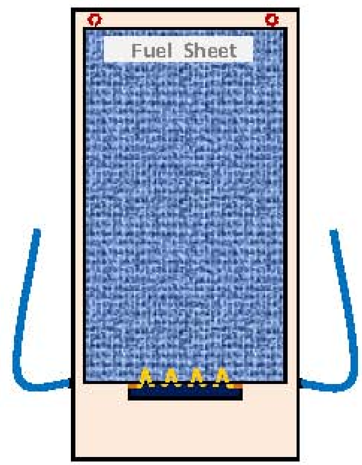
- Tests conducted in Zero Gravity Facility at NASA-GRC for Ultem 1000, Nomex, and Mylar
  - 5.2-sec limits samples to thin materials

Lunar-g Maximum Oxygen Concentration

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

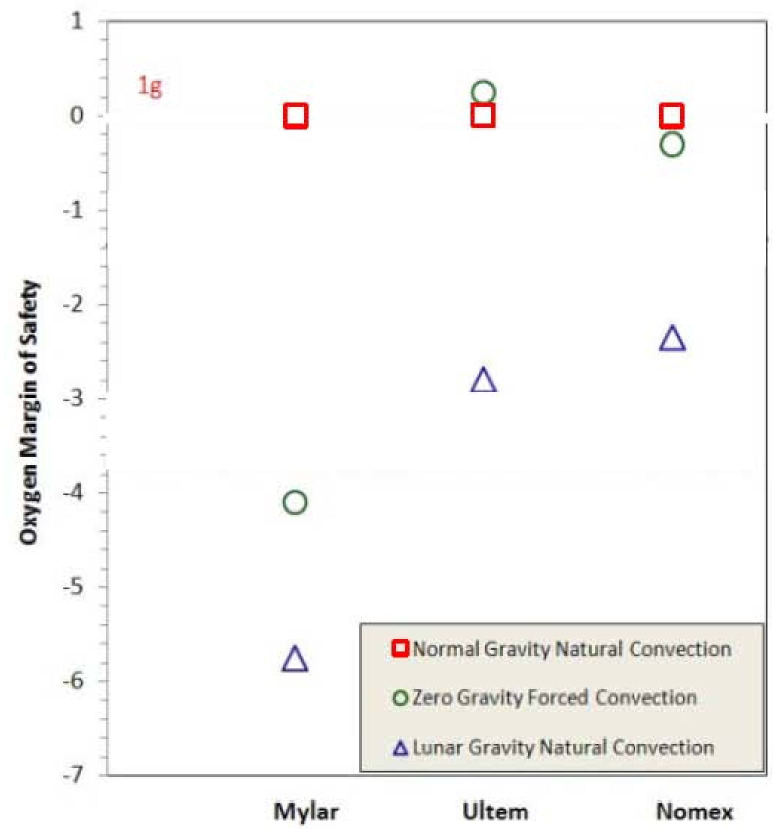


- Fuel sample is 5 cm wide by 6 cm long.



Zero-g and Lunar-g MOC Results

- Tests were conducted at WSTF (normal-g) and GRC (Lunar-g) to quantify changes in the MOC for Nomex, Mylar, and Ultem
- Conditions run in Lunar-g burned at both the *normal gravity MOC* and at the *zero-g convective MOC*
  - Lunar-g flammability appears more like zero-g rather than 1-g
  - Cessation of ventilation flow is not effective
- Significant impact on a fire safety strategy, especially if the need for fire detection and suppression is dictated by the difference between the MOC and atmosphere of use.



➢ ***How large can a fire get and how long will it take a fire to get that large?***

FPDS Major Accomplishments

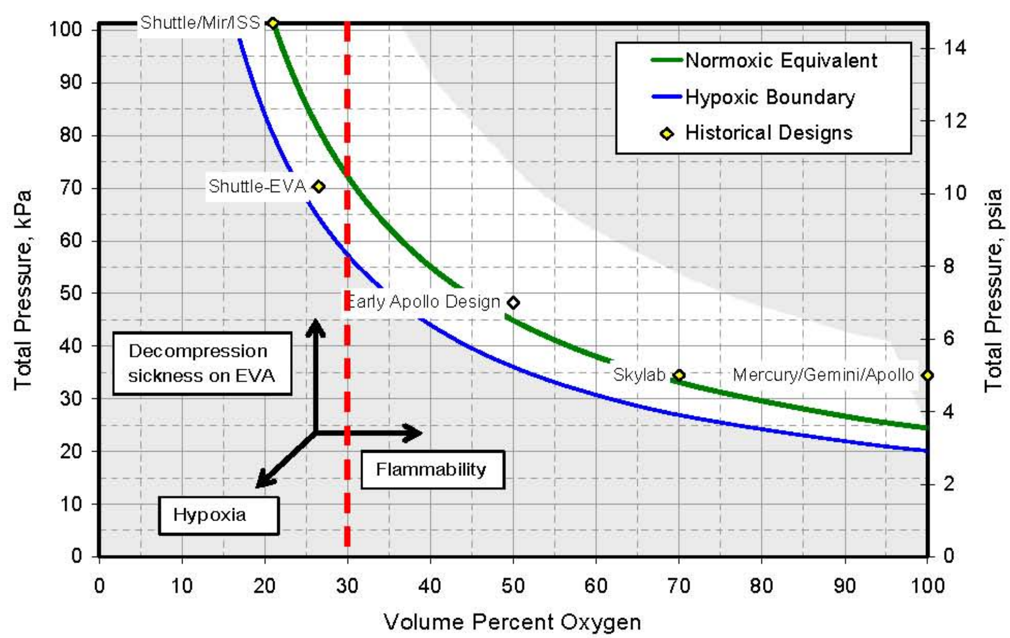
- Low-g Maximum Oxygen Concentration tests
  - For the first time, quantifies the difference between 0-g, Lunar-g and 1-g MOC for relevant materials
- Flammability correlations as functions of pressure, velocity, and $\%O_2$
  - *What is the impact on material flammability as you trade oxygen concentration and pressure?*
- Ignitability of materials increases as pressure decreases
- Fire Detection
  - Interpretation of results for the Smoke Aerosol Measurement Experiment (and –Reflight)
  - Development of the Multiparameter Aerosol Scattering Spectrometer
  - Simulation of smoke detector activation
- Water mist fire extinguisher
  - Sufficiently raised TRL for extinguisher to warrant a change in Orion baseline
- Post-fire Clean-up
  - Development of a standard challenge
  - Suite of instrumentation (from SBIRs)

Spacecraft Habitable Atmosphere Trades

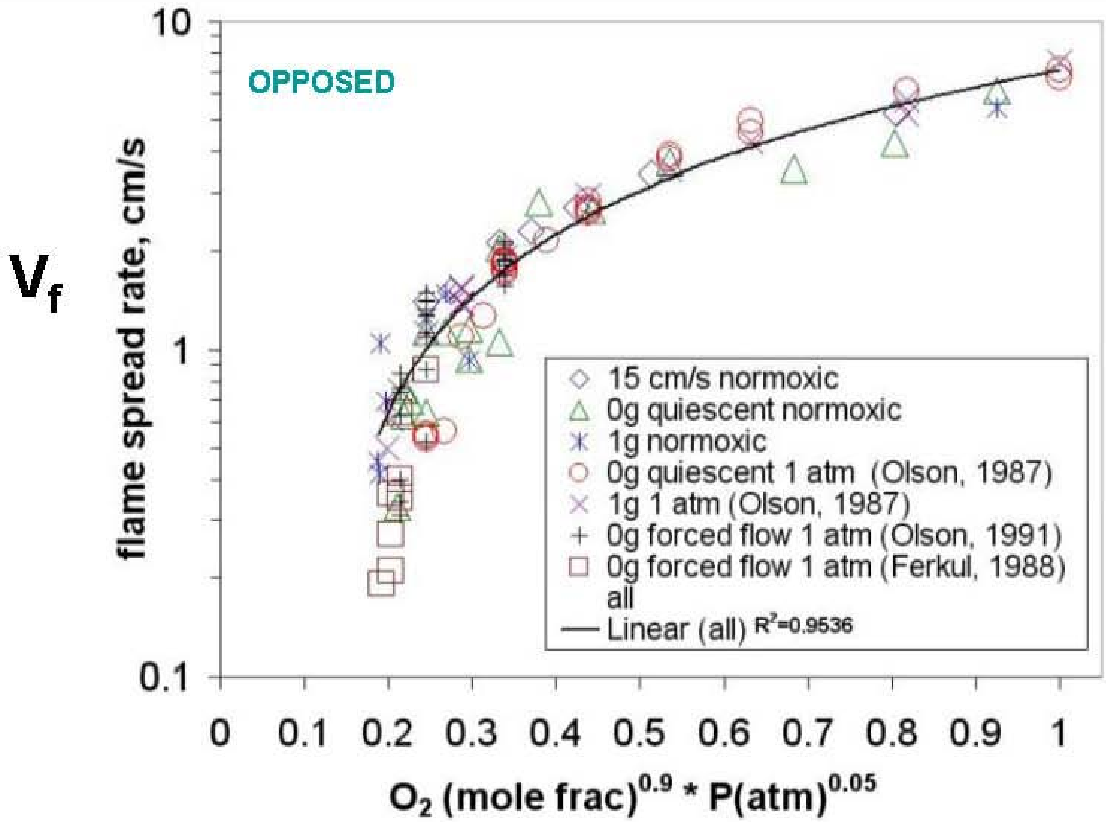
- In 2005, the Exploration Atmospheres Working Group performed a detailed trade study of potential atmospheres for exploration missions
  - Experts in space medicine and physiology, mission operations, and vehicle and habitat systems
- Traded against decompression sickness (pre-breathe time), hypoxia and material flammability
- *What is the quantitative effect of elevated mole fractions of oxygen and reduced ambient pressure on material flammability in low- and partial-gravity?*

or

- *How large can a fire get and how long will it take a fire to get that large?*



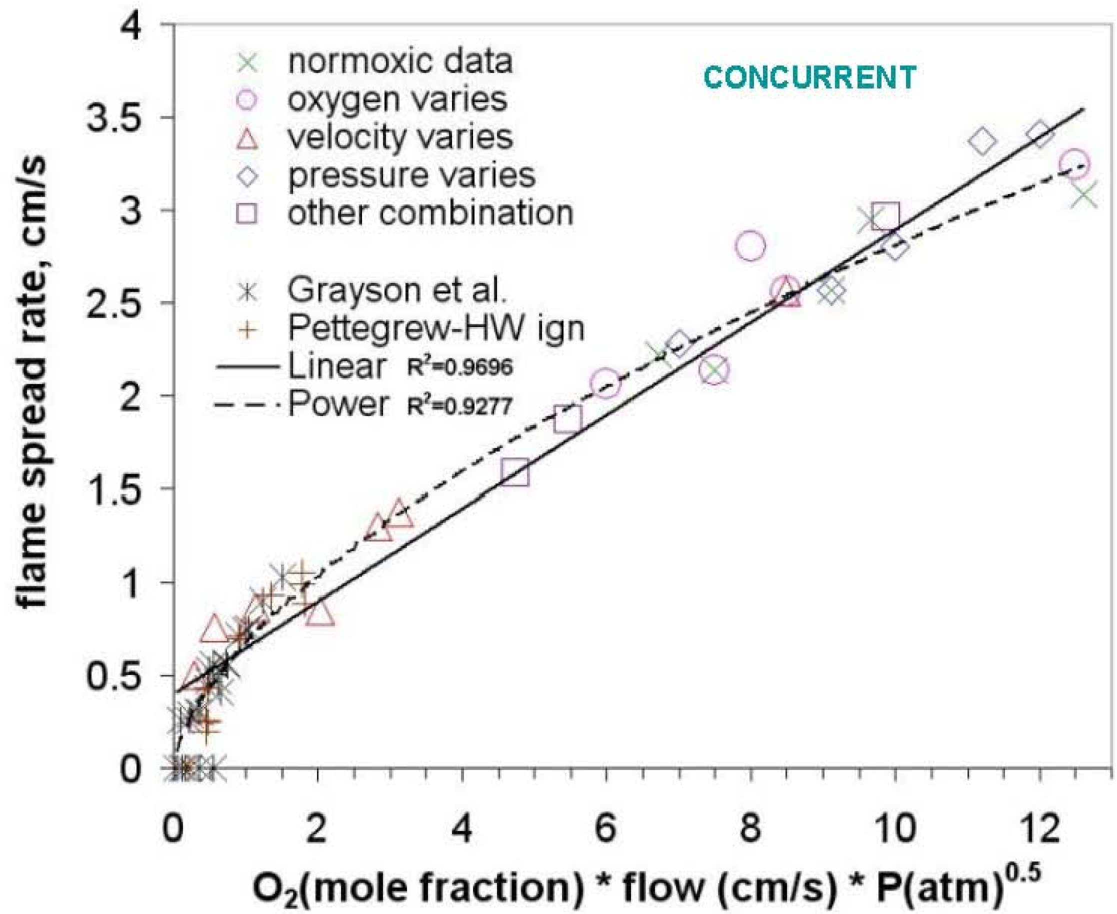
Opposed Flow Flame Spread Correlation



Flame spread data for Kimwipes, fit to an oxygen-pressure correlation [Magee and McAlevy, 1971] for opposed flow under a variety of atmospheric and gravitational conditions.

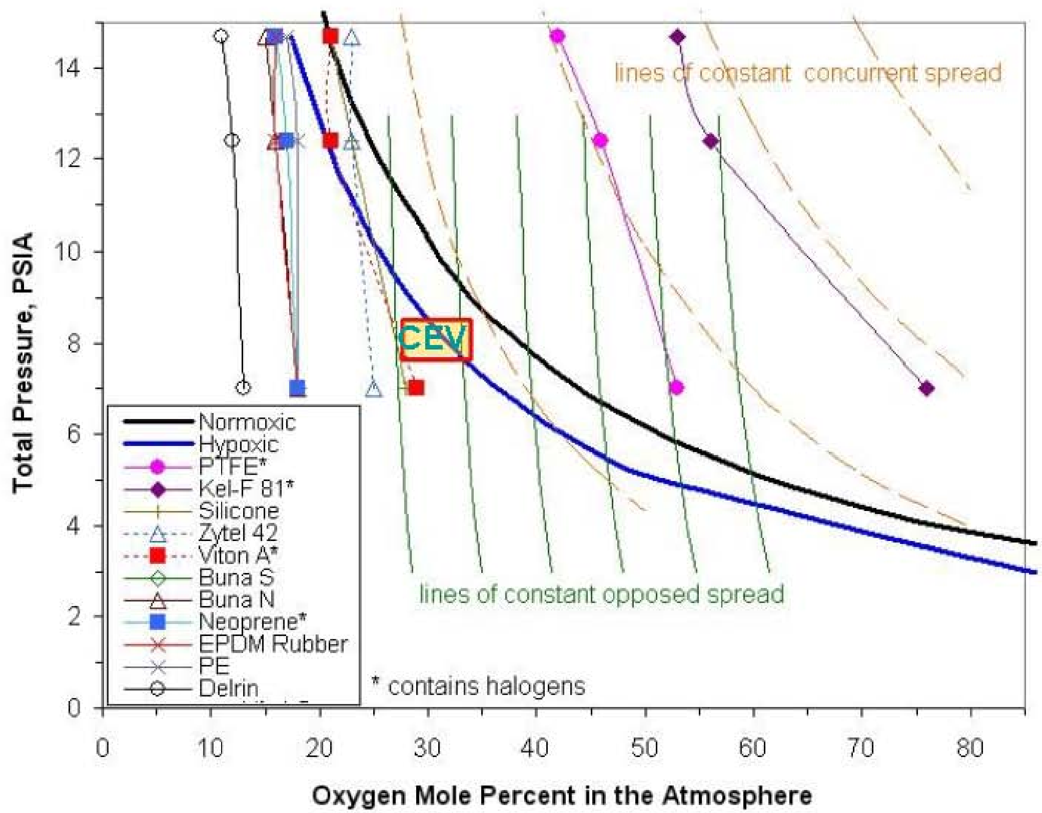
Concurrent Flow Flame Spread Correlation

V_f



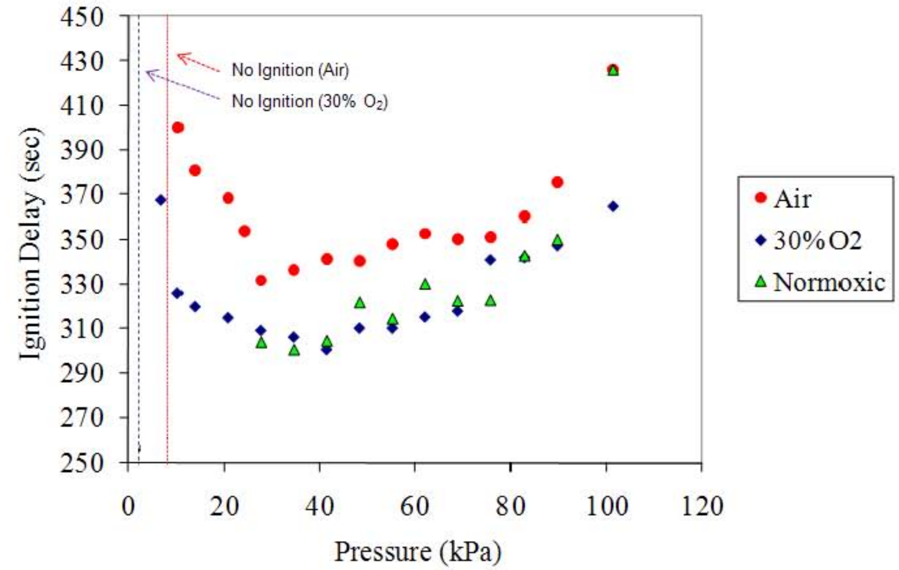
Predicted vs Measured Trends in Flammability

- **MOC values from NASA Test 1 resemble opposed spread trends**



Ignition in Spacecraft Atmospheres

- Tests by researchers at *University of California at Berkeley* have shown that the time required for a material to ignite after it has been exposed to an external heat flux (ignition delay time) decreases with decreasing pressure and increasing oxygen concentration.
  - ignition is easier at low pressures and increased oxygen concentrations
- If a low-g spacecraft fire ignites easier and has a lower oxygen flammability limit …



Ignition delay time as a function of pressure for different oxygen/nitrogen mixtures. *The effect of pressure on ignition is larger than oxygen concentration. The minimum in the curves represents a balance between transport and chemical effects.*

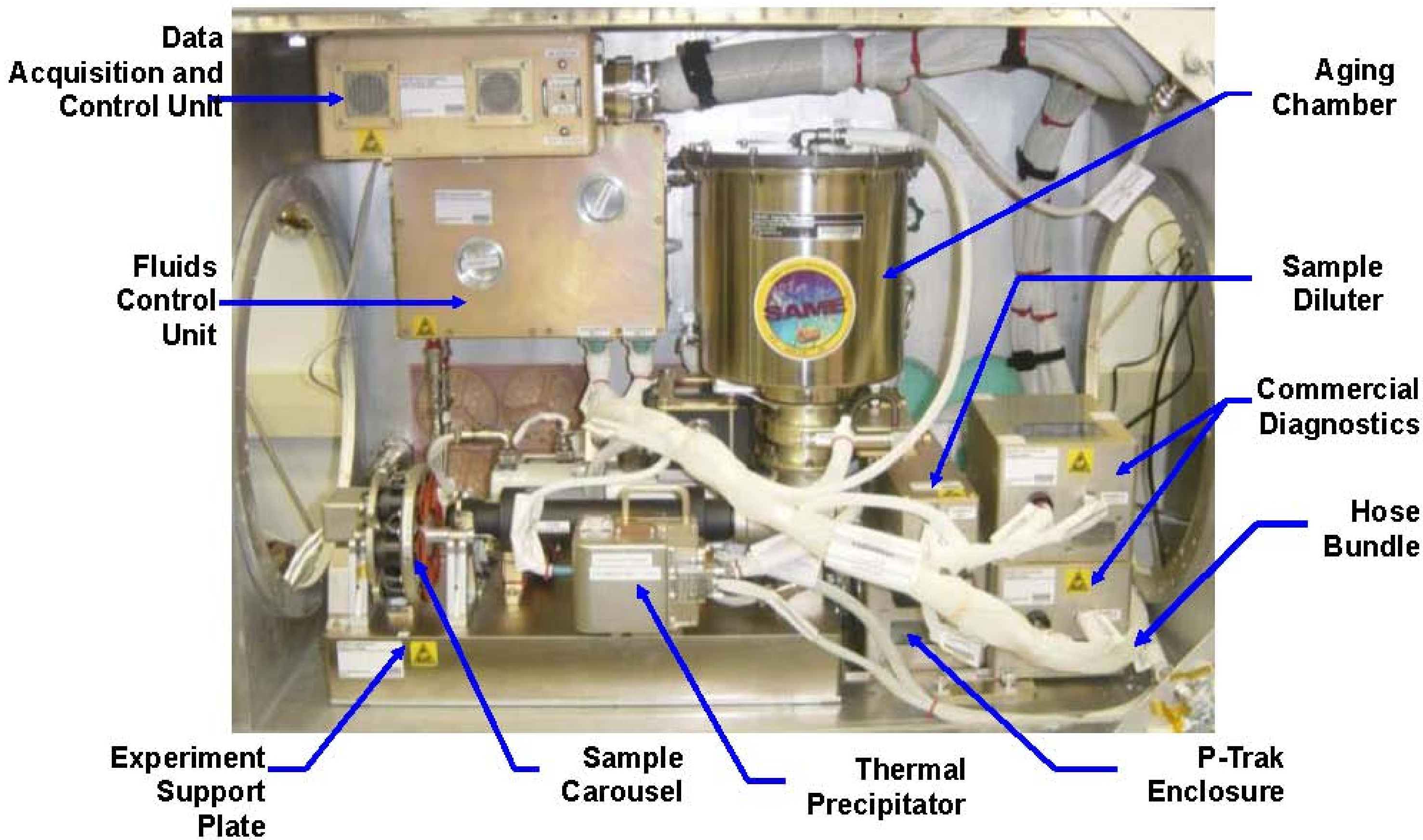
➢ ***How large can a fire get and how long will it take a fire to get that large?***

FPDS Major Accomplishments

- Low-g Maximum Oxygen Concentration tests
  - For the first time, quantifies the difference between 0-g, Lunar-g and 1-g MOC for relevant materials
- Flammability correlations as functions of pressure, velocity, and $\%O_2$
  - What is the impact on material flammability as you trade oxygen concentration and pressure?
- Ignitability of materials increases as pressure decreases
- Fire Detection
  - *Interpretation of results for the Smoke Aerosol Measurement Experiment (SAME) and SAME-R (Reflight)*
  - *Development of the Multiparameter Aerosol Scattering Spectrometer (MPASS)*
  - *Simulation of smoke detector activation*
- Water mist fire extinguisher
  - Sufficiently raised TRL for extinguisher to warrant a change in Orion baseline
- Post-fire Clean-up
  - Development of a standard challenge
  - Suite of instrumentation (from SBIRs)

Smoke Aerosol Measurement Experiment

- SAME in MSG mockup



SAME Operations

- SAME launched on STS-118 in August 2007
- Operated in the Microgravity Science Glovebox in September and October 2007 by Expedition 15
- 30 Samples of 5 Materials Distributed in 5 Carousels
  - Silicone Rubber
  - Teflon
  - Kapton
  - Lampwick (cellulose)
  - Dibutyl phthalate (DBP)
- 47 total test points
- Samples and TEM grids were returned on STS-120

Summary of SAME results

- Lampwick and silicone produced pyrolysis aerosols similar to those associated with terrestrial early warning fire signatures.
  - After a 720 second aging period, the CMDs increased significantly
- Teflon samples produced somewhat smaller particles than lampwick and silicone and similar evolution with aging
  - not significantly differed from particulate observed terrestrially
  - somewhat inconsistent with the larger particle sizes that were qualitatively observed in the CSD experiment
- Kapton aerosols were relatively small, roughly a third of the nominal value for terrestrial signatures (190 nanometers)
  - even after aging, the CMD remained roughly 20% smaller than this value

➢ Based on the SAME results, possible fire signatures occur in both large and small particle size regimes
  - Problematic for conventional ionization and optical scattering fire detectors

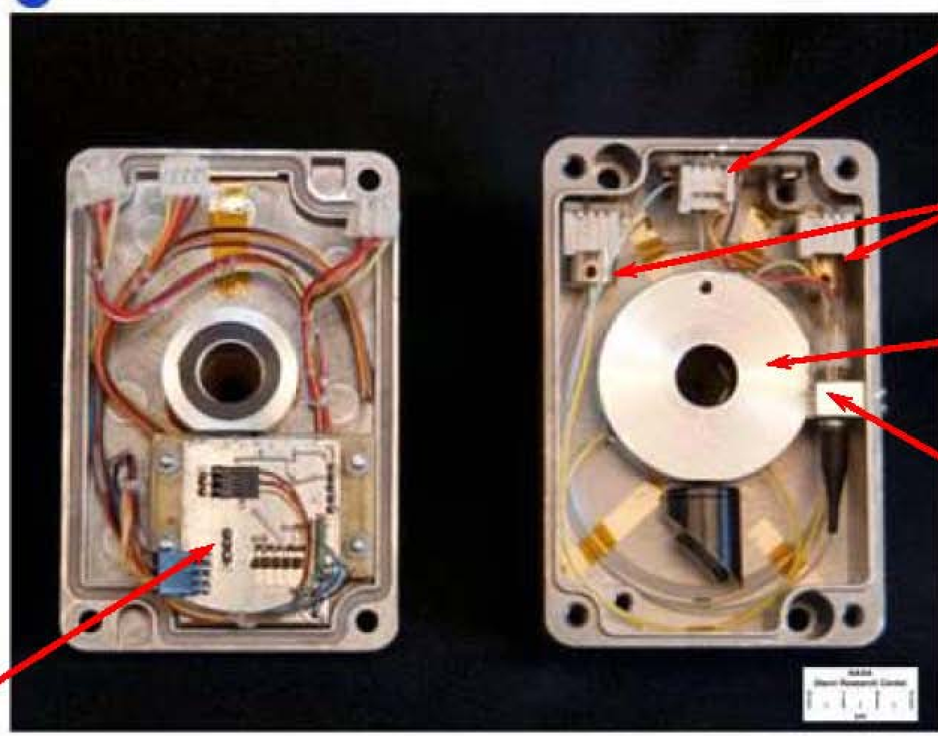
➢ **Size selective smoke detection will improve reliability and false alarm rejection.**
  - **Classifying the particles or by measuring multiple moments**

Motivation for an Improved Smoke Detector

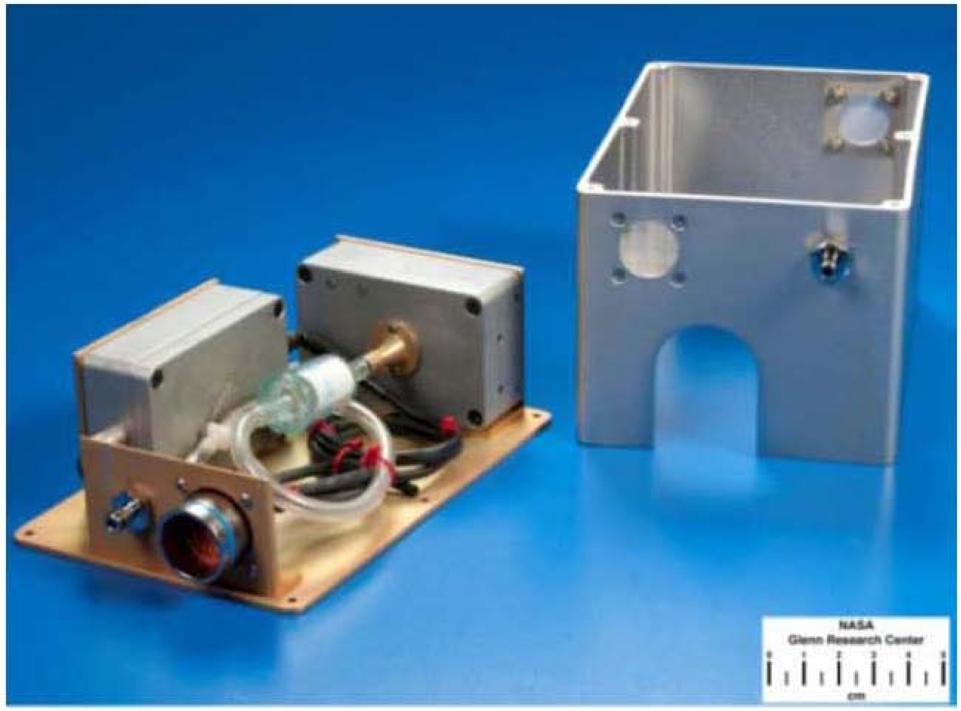
- With increased knowledge of low-g smokes, we have the opportunity to create smoke detectors having increased capabilities.
- Reliable and prompt identification of evolving fire hazards requires sensors of adequate sensitivity,
  - provisions to exclude false events with high probability
- The inclusion of additional sensors, such as gas-phase composition, may prove to be an important component
  - An alternate approach is to maximize the information available from the particulate aerosol.
- The current detector development makes use of optical scattering due to the richness of information available from particle-light interactions
  - Supported in part by the Fire Prevention, Detection, and Suppression (FPDS) project within Exploration Tech Development Program (ETDP)
- A re-flight of the SAME experiment (SAME-R) presented the opportunity to demonstrate additional diagnostic instruments.
- The resulting capability could augment the science return of SAME by providing additional characterization of the test aerosols.

Construction of MPASS Sensor

SAME-R flight sensor



MPASS SAME-R Flight Hardware



- **In the SAME hardware, the MPASS mimics a TSI DustTrak**
  - physical size, connections, and communication

Smoke Transport and Detector Activation in Orion

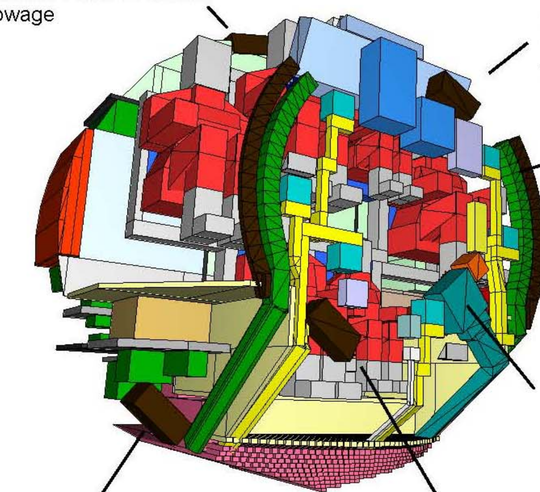
Objective

- Apply tools developed to simulate smoke transport and fire spread in terrestrial systems to exploration systems
- Understand how fire detector activation times are affected by: sensor location, size of fire, ventilation flows, and obstructions
- Fire Dynamic Simulator (FDS) developed and supported by NIST
  - Has become a widely-used tool for fire analysis
  - Developers have a grant to verify the large-eddy simulation capabilities of this tool for low-g

Procedure

- Smoke originates from a cable interface
- Transported to detector via module air flow
- Calculate time-to-alarm for various fire locations

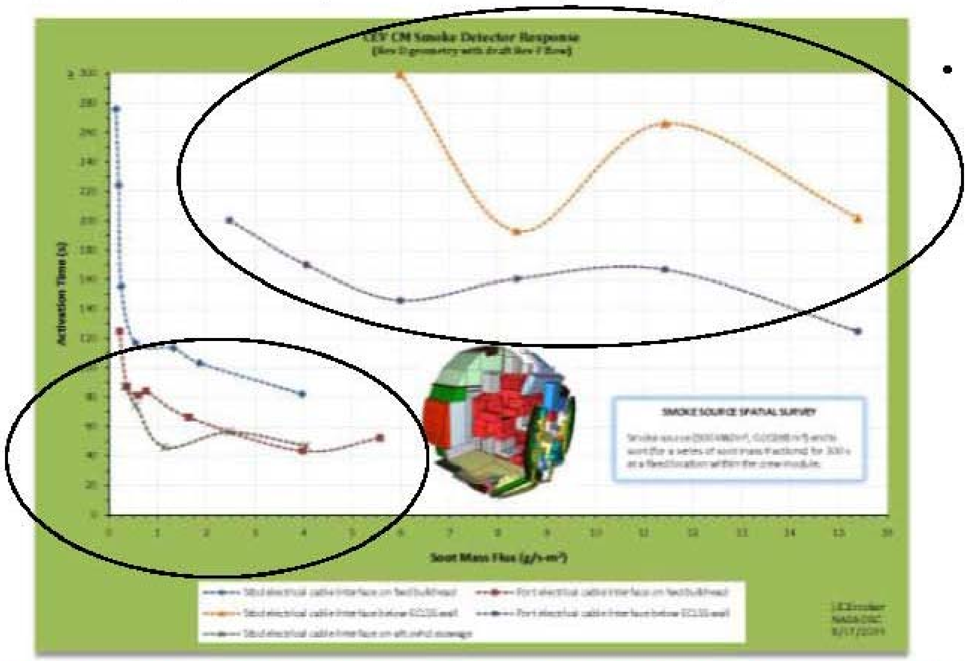
FDS Representation of the Orion Crew Module



Smoke Transport and Detector Activation in Orion

- Simulations run for 5 minutes computational time (or until smoke detector alarms)
  - Requires over 100 hours clock time
- Smoke sources on forward bulkhead are detected within no more than 120 sec
- Sources behind ECLSS wall require 160 sec (minimum) to alarm

- **Open cabin fire sources**



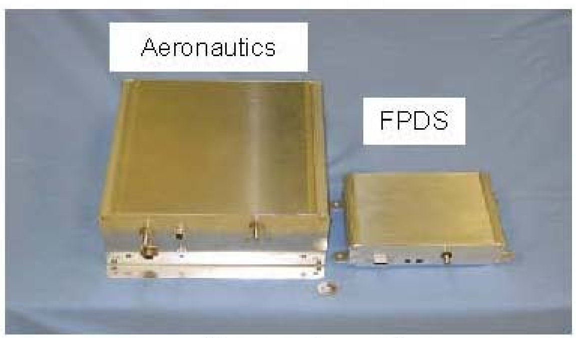
- **Hidden fire sources**

➢ ***How fast does a low-g fire grow and how big does it get?***

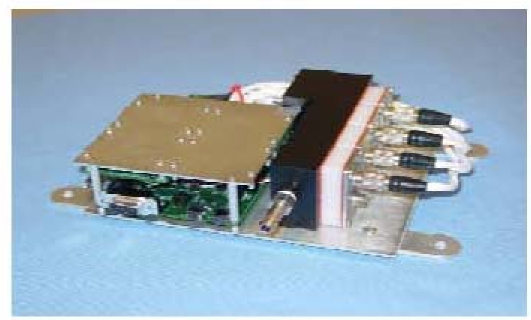
Multiparameter Fire Detection System

- System features include:
  - Four chemical sensors: CO, H_2/HC, CO_2
  - Particulate sensor: IMS cell or two-moment optical scattering sensor
  - Two environmental sensors: humidity and pressure
  - Small pump for air flow
  - Core hardware for power, acquisition, analysis
  - Battery operation and wireless transmission possible

➢ Recent work has focused on the low-concentration CO sensor



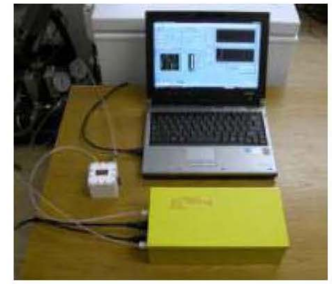
Comparison of aeronautics fire detector (10" x 10" x 4.5") to FPDS fire detector (7" x 5.9" x 2.1")



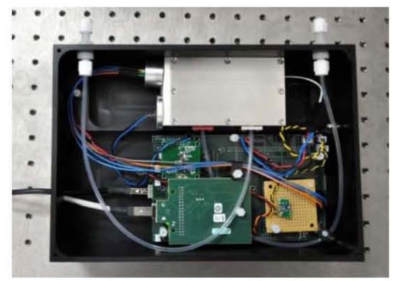
Miniaturized multiparameter fire detection system

Advanced Fire Detection Technologies

- **Low-concentration (< 5 ppm) CO sensor**
  - Solid State: OSU/Makel/GRC
  - LD-PAS: SBIR Phase III - Vista Photonics
  - Integrated VCSEL-WMS: SBIR Phase II – Vista Photonics
  - QCL absorption: SBIR Phase I – Maxion, Inc.
    - absorption measurement at 4.610-μm



LD-PAS detector for CO. *The operation of the instrument is monitored on the computer.*



VCSEL-WMS CO detector. *2.3 mm VCSEL absorption-based sensor (0.5 ppm CO)*

- **HF, HCN, HCl sensor**
  - LD-PAS: SBIR Phase III - Vista Photonics
  - Solid state sensors – GRC and Makel Engineering

- Evaluation of post-fire environments and sensors will determine applicability for post-fire monitoring

LD-PAS detector for HF, HCl, and HCN. *The data is shown in the display on the front panel.*

FPDS Major Accomplishments

- Low-g Maximum Oxygen Concentration tests
  - For the first time, quantifies the difference between 0-g, Lunar-g and 1-g MOC for relevant materials
- Flammability correlations as functions of pressure, velocity, and %O_2
  - What is the impact on material flammability as you trade oxygen concentration and pressure?
- Ignitability of materials increases as pressure decreases
- Fire Detection
  - Interpretation of results for the Smoke Aerosol Measurement Experiment (SAME) and SAME-R (Reflight)
  - Development of the Multiparameter Aerosol Scattering Spectrometer
  - Simulation of smoke detector activation
- Water mist fire extinguisher
  - *Sufficiently raised TRL for extinguisher to warrant a change in Orion baseline*
- Post-fire Clean-up
  - Development of a standard challenge
  - Suite of instrumentation (from SBIRs)

Fire Extinguisher Development

Issue

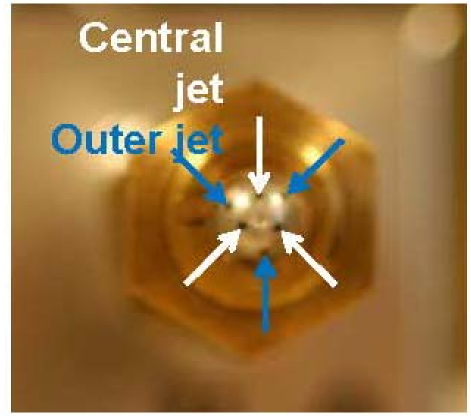
- Even though fine water mist was recognized as having beneficial characteristics for spacecraft fire suppression, it was not baselined by contractor trade studies because of the lower TRL (relative to the presumed TRL of COTS extinguishers)
- Received some FTE from CxP, supplemented by ETDP to advance TRL
- Worked with JSC Orion and ADA Technologies, Inc.

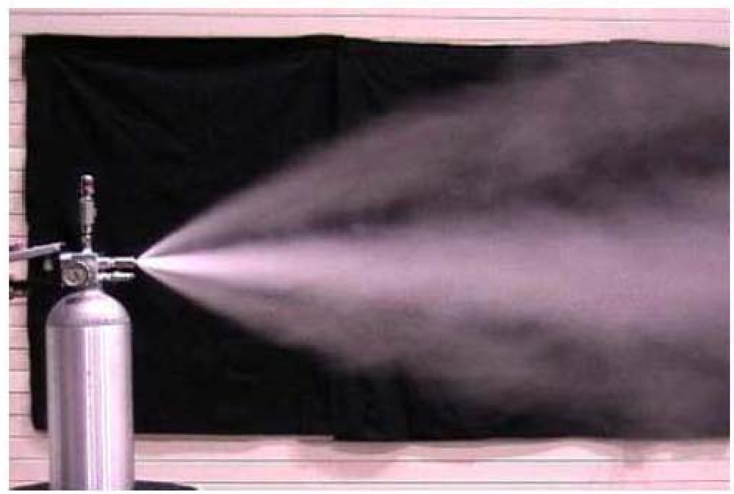
Fine Water Mist Fire Extinguisher

- Cylinder is 5.25” diameter, 14.25” tall
- Charge with 1000 psi N_2
- Holds ~900 cc water
- Produces water droplets 20-50 µm in diameter

Fine Water Mist Fire Extinguisher

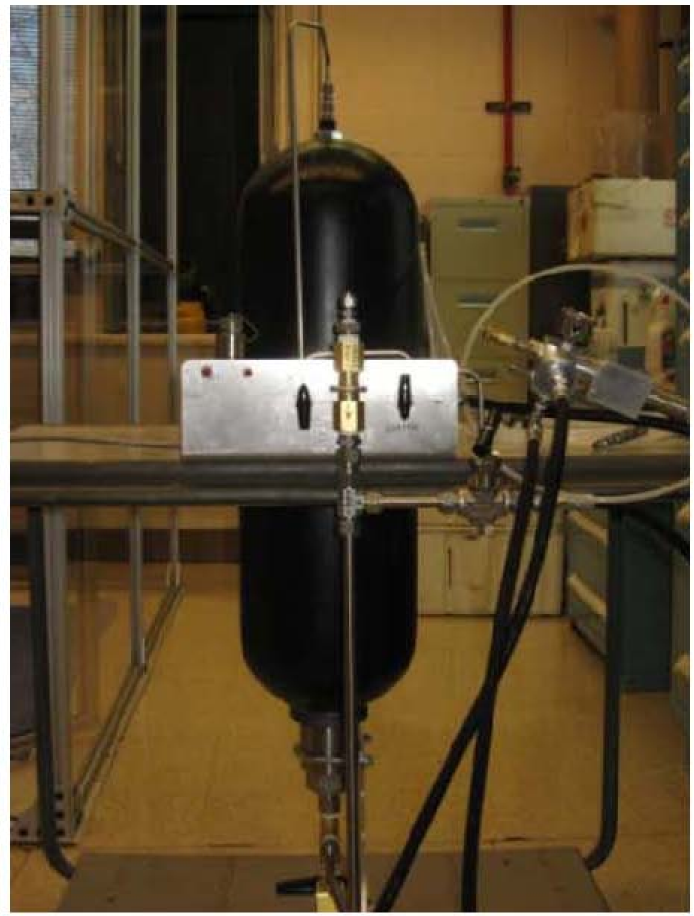
- Nozzle has six jets
  - Three central jets
  - Three outer jets





Steady Flow Water/Gas Supply Cart

- System developed for long discharge times and constant pressure operation
  - Good for measuring droplet diameter and velocity, mass flow rate as a function of system pressure
- Use 5 gal (18.9 L) tank containing water and nitrogen
  - Holds enough water for four minutes of use
- Connects to hand piece (valve, nozzle) similar to hand extinguisher
  - Cart uses shop-air driven piston instead of hand lever to open valve

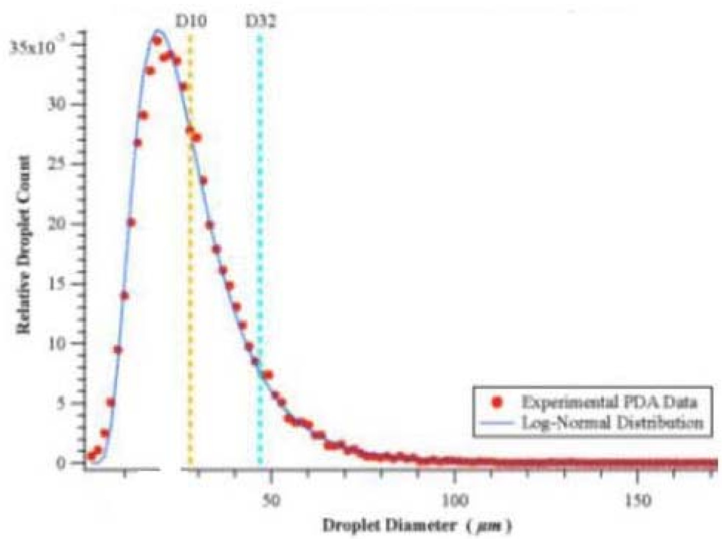


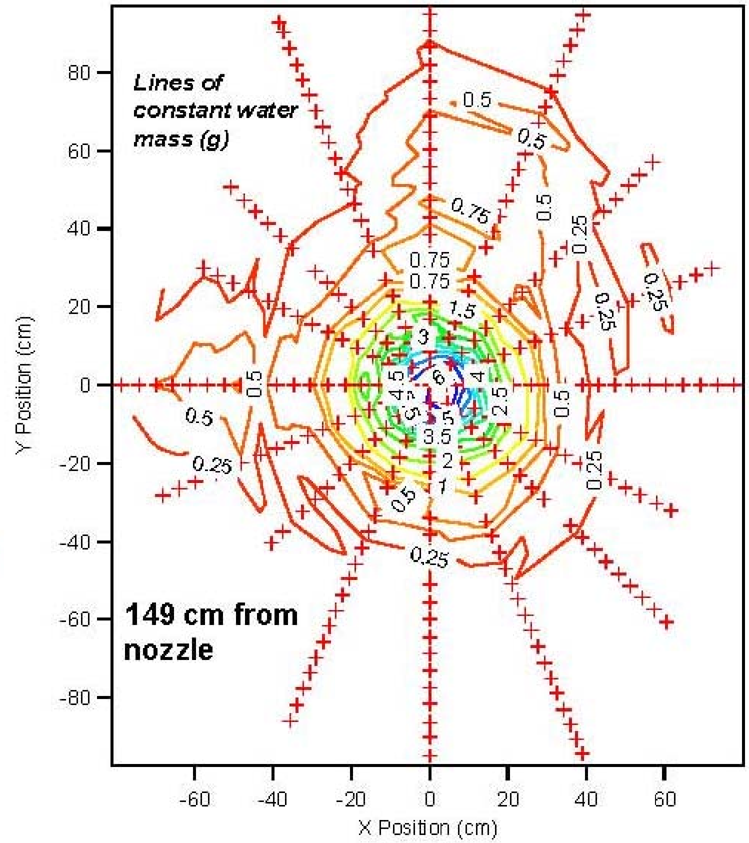
Droplet Diameter and Velocity Measurements

- Use Dantec Dynamics PDA system to make measurements
  - System reports individual measurements, we calculate ensemble values
  - Velocity
    - Mean and standard deviation
  - Droplet diameter
    - Mean, standard deviation, second and third moments, Sauter diameter
- Mount nozzle on three-axis translation stage
- Current measurements made along axial centerline and radially at 28 cm below nozzle

Droplet Size and Dispersion Pattern

- ***SBIR Prototype Extinguisher***

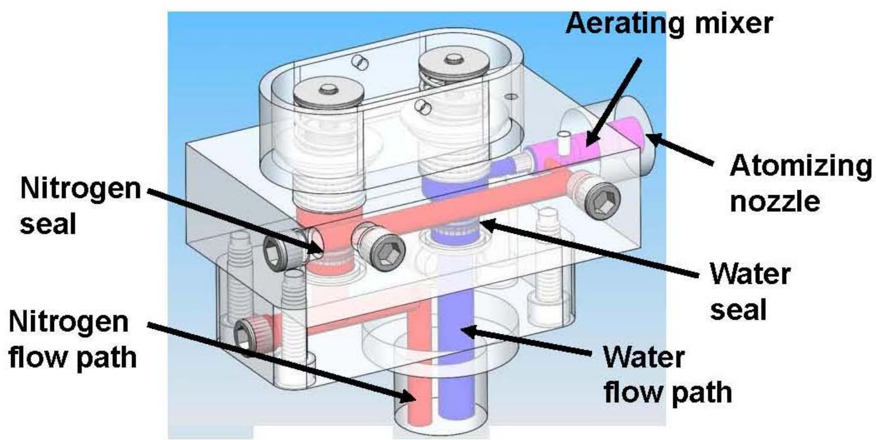




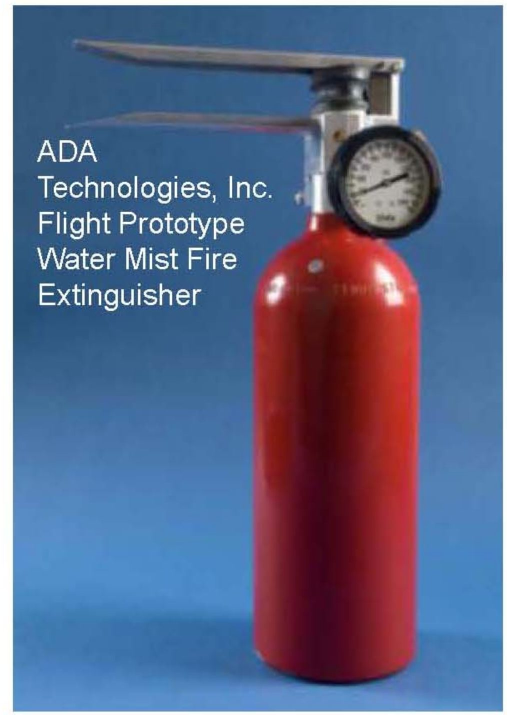
- Center orifice
- 28 cm downstream of the nozzle
- 6.5 MPa

Fine Water Mist Fire Extinguisher

- Worked with JSC Engineering and ADA Technologies, Inc. to develop a flight prototype fire extinguisher (funded by JSC)
- Fire tests at ADA Tech/Colorado School of Mines are on-going
- Prototype will then come to GRC for drop size characterization and dispersion testing
- Develop Product Specification Document



➢ ***How large a fire does a spacecraft extinguisher have to put out?***



FPDS Major Accomplishments

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- Water mist fire extinguisher
  - Sufficiently raised TRL for extinguisher to warrant a change in Orion baseline
- Post-fire Clean-up
  - *Development of a standard challenge*
  - *Suite of instrumentation (in-house and SBIR Program)*

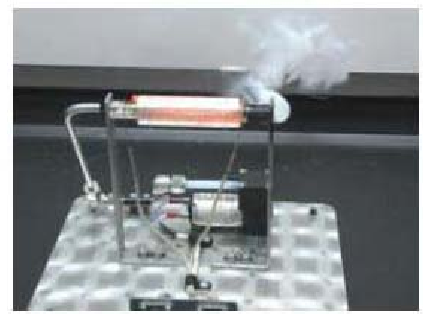
Post-Fire Cleanup

- The most important requirement in developing a post-fire cleanup process is to specify the state of the atmosphere to be scrubbed
  - pressure, temperature, and composition
- With WSTF, FPDS personnel helped develop a suitable post-fire challenge

Sample Composition

Polymer	Percent Composition
Silicone	20.8
Epoxy	20.8
Polypropylene	15.1
Polycarbonate	8.7
PTFE	6
Polyimide	5.7
Polyvinylchloride	5.7
Polyurethane	4.9
Polyphenylene Oxide	4.9
Phenol formaldehyde	3.8
Polysulfone	1.8
Polyester	1.8
Total	100%

Pelletized fuel sample



Sample heater

Post-Fire Cleanup Test Protocol

- Post-fire test conducted in a glovebox facility at WSTF
  - evaluate smoke and contaminant scrubbing
  - mask filters
  - evaluate CO and acid gas monitoring technologies

Typical Spacecraft Mix
Low Visibility, significant smoke produced

➢ ***Does this represent a realistic post-fire environment?***

Dedicated Post-fire Response Glovebox (March 2009)

Wet Trap

Ion Chromatograph

Status of FPDS Technologies

Technology Readiness Level

TRL 1 Basic principles observed and reported

TRL 2 Technology concept and/or application formulated

TRL 3 Analytical and experimental critical function and/or characteristic proof-of-concept

TRL 4 Component and/or breadboard validation in laboratory environment

TRL 5 Component and/or breadboard validation in relevant environment

TRL 6 System/subsystem model or prototype demonstration in a relevant environment (ground or space)

TRL 7 System prototype demonstration in a space environment

TRL 8 Actual system completed and “flight qualified” through test and demonstration (ground or space)

TRL 9 Actual system “flight proven” through successful mission operations

Status of FPDS Technologies

Capability Readiness Level

- A Capability is defined as a set of systems (or system of systems) with associated technologies & knowledge that enable NASA to perform a function (e.g. scientific measurements) required to accomplish the NASA mission.
- A Capability needs to be demonstrated and qualified, just as a technology does, in both laboratory and relevant environments.
  - The infrastructure and knowledge (process, procedures, training, facilities) of the Capability needs to be
    - demonstrated and qualified in both laboratory and relevant environments and
    - available to support the Capability in order for it to be considered mission-ready.

5 — **Capability Operational Readiness**

4 — **Integrated Capability Demonstration in Operational Environment**

3 — **Integrated Capability Demonstration in Relevant Environment**

2 — **Sub-Capabilities* Demonstrated in Relevant Environment**

1 — **Concept of Use defined, Capability, Constituent Sub-capabilities* and Requirements Specified**

*** Sub-capabilities include technologies, infrastructure, and knowledge (process, procedures, training, facilities)**

Status of FPDS Technologies

Technology	Responsible Party	TRL/CRL	Assessment and Future Plans
Material Flammability (capability to use low-g material flammability as acceptance criteria)			
Maximum Oxygen Concentration	GRC	CRL 2	More materials need to be tested. Need to verify at larger length and time scales
Effect of pressure and %O_2 on flammability and ignition	GRC	CRL 2	More materials need to be tested. Need to verify at larger length and time scales
Fire Detection			
Multiparameter Aerosol Scattering Spectrometer	GRC	TRL 5-6	Flight instrument has been produced, experiments on-going with results TBD
Solid-state multiparameter gas sensors	GRC/Makel Engineering	TRL 5	Fire detection is mature.
Smoke detector activation modeling	GRC	CRL 3	Capability demonstrated but not used/verified in an operational environment
Fire Suppression			
Water mist fire extinguisher	ADA Technologies, Inc.	TRL 5-6	Tests are on-going. Will be TRL 6 when characterization for Product Specification Document is complete
Post-fire Cleanup			
Post-fire test facility	WSTF/JSC/GRC	CRL 3	Tests have been conducted. Environment must be characterized and verified against a spacecraft post--fire environment
Low-concentration CO			
Solid-state sensors	GRC/Makel Engineering	TRL 3-4	Rounds of testing and improvements of prototype
LD-PAS: SBIR Phase III	Vista Photonics, Inc.	TRL 5	Successfully evaluated in post-fire test facility
Integrated VCSEL-WMS: SBIR Phase II	Vista Photonics, Inc.	TRL 4	Successfully evaluated in JSC Toxicology Lab
QCL absorption: SBIR Phase I	Maxion Technology	TRL 2	Phase I ending July 31 with promising results
HF, HCl, HCN			
LD-PAS: SBIR Phase III	Vista Photonics, Inc.	TRL 5	Evaluated in post-fire test facility. Questions about presence of gases.
Solid-state sensors	GRC/Makel Engineering	TRL 3-4	Prototypes evaluated in laboratory. Under development

To be Completed in FY10

- Testing of post-fire sensor suite at WSTF (week of August 16)
  - VCSEL-WMS for CO
  - HF via integrating sphere
  - LD-PAS for HCN and HCl
- Characterization of drop sizes and spray dispersion from ADA Technologies, Inc. flight prototype water mist fire extinguisher (end of August)
- Accumulation of documents on ETDP close-out checklist
  - Technical papers
  - Risk disposition and status

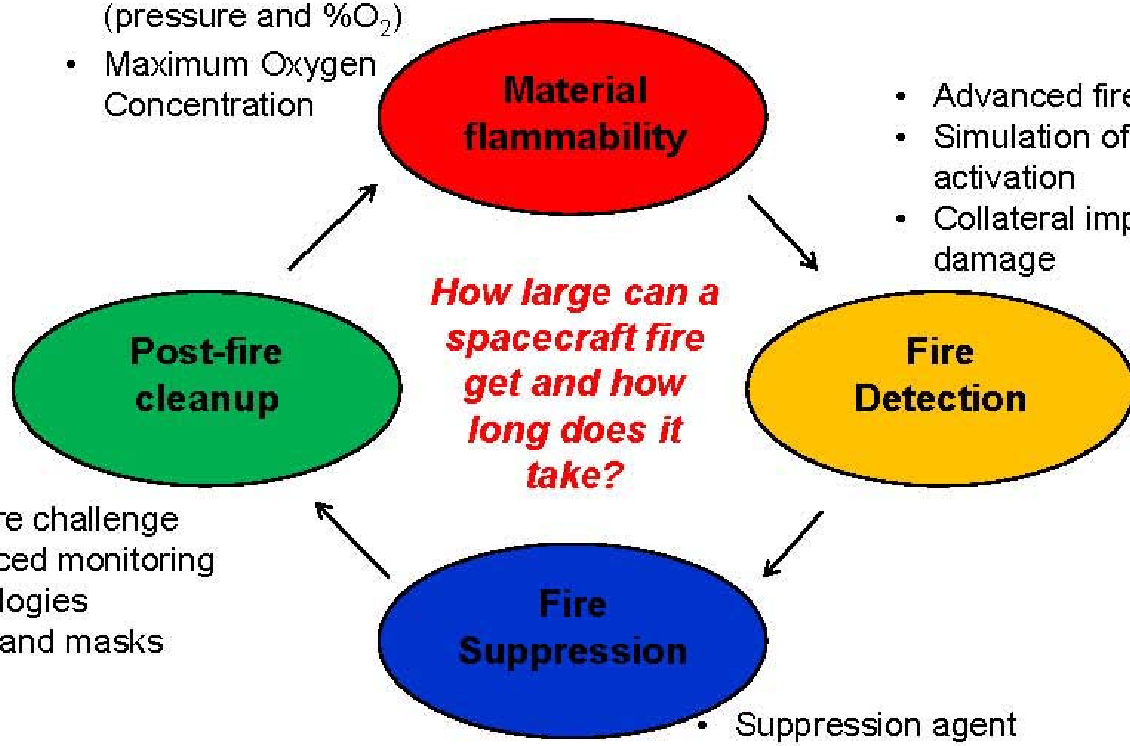
Lessons Learned

- Technology assessments are required throughout the project/program lifetime
  - "Who's doing what" changes after several years of implementation
  - Assessment of relevance and consistency is needed across customers' programs
- Timing is important and needs to be taken into account
  - Information about fire safety technologies is needed at System Requirements Review or shortly thereafter
    - Consistent data is needed for early trade studies
    - Hardware could be as late as CDR
- Consider development time/window in prioritization
  - Balance between near-term needs and far-term needs
- When rated against other life support systems, FDS will always rate lower
  - But it will be on the vehicle and the technology will impact other systems
- Within ETDP, we've had a chance to develop integrated fire safety technology development within NASA

Spacecraft Fire Prevention, Detection, and Suppression Design Processes

- Habitable atmosphere (pressure and $\%O_2$)
- Maximum Oxygen Concentration

- Advanced fire detectors
- Simulation of fire detector activation
- Collateral impacts and damage



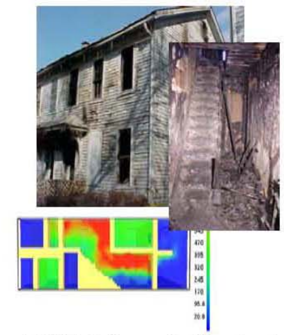
- Post-fire challenge
- Advanced monitoring technologies
- Filters and masks

- Suppression agent characteristics
- Effectiveness
- Mass and volume

Large-Scale Fire Demonstration Experiment

- Utilize/recycle the current automated servicing vehicles as a platform for fundamental research free-flyer tests and large scale fire tests
- After vehicle is loaded with trash, install other free flyer payloads or, in the case of a fire experiment, igniters and fire sensors.
  - Allow the free flyer experiment to complete its testing and then trigger the fire event after the vehicle has performed its deorbit burn
- Technical issues involve size of experiment, telemetry, and safety

FAA full-scale aircraft test



NIST full-scale fire test

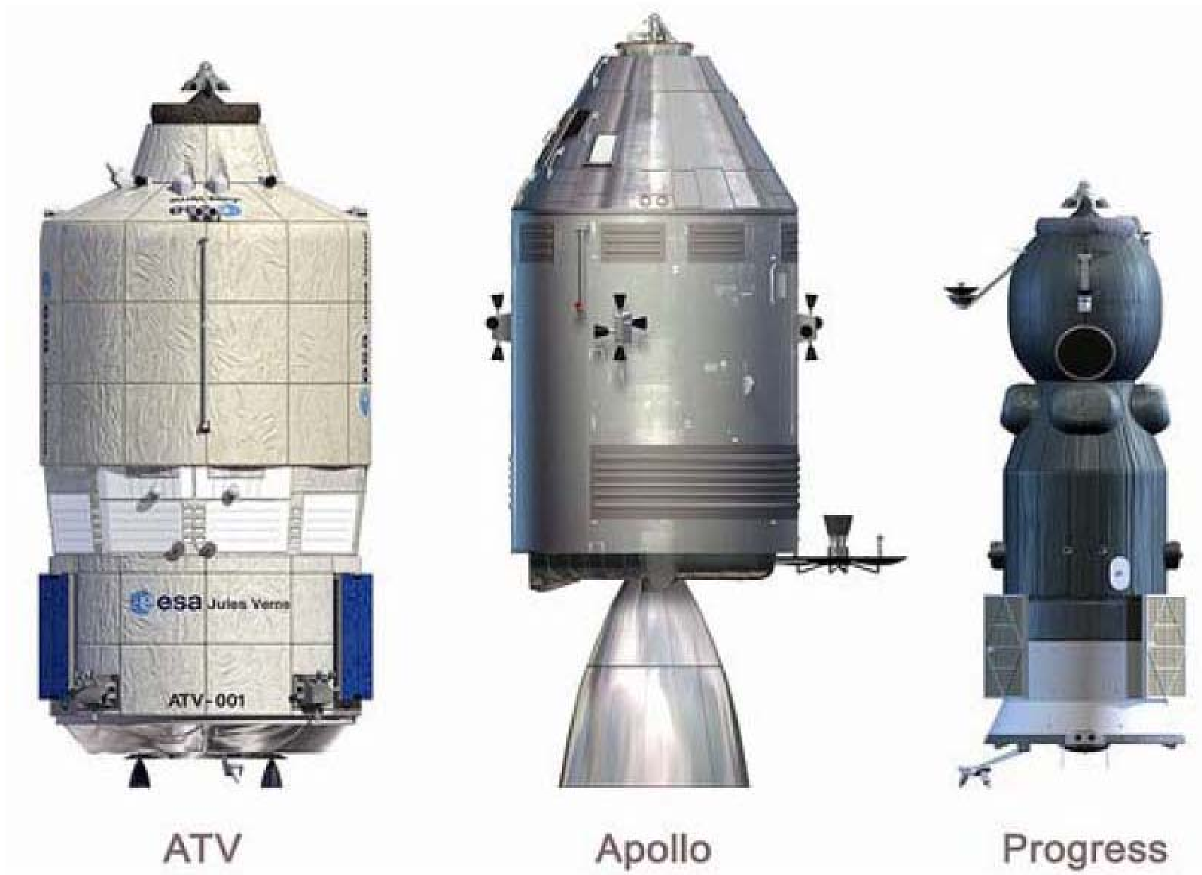
Ex-USS Shadwell

Submarine Fire Facility

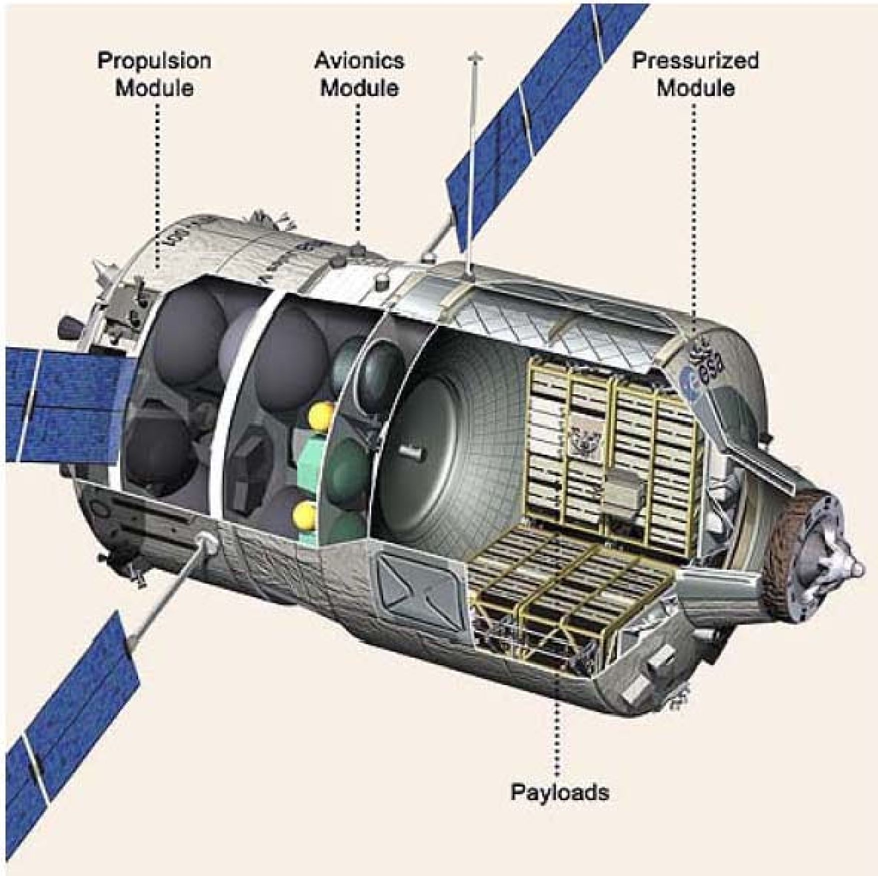
Naval Research Laboratory

Coal dust test explosion

Relative size of ATV, Progress, and Apollo



ATV interior



Fire Prevention, Detection, and Suppression

Summary

- Implementation of the CxP has focused many of the fire safety technology development efforts directly onto the hardware that will be needed for exploration spacecraft
- FPDS has implemented an integrated approach to fire safety
  - Addressed areas where uncertainties have been identified
  - Brought ground-based fire safety technologies and processes to bear on spacecraft
- New knowledge and technology have been rapidly infused into CxP requirements and even baselined in spacecraft designs
  - Critical design and development of flight hardware to follow
- Future emphasis will be on flammability, detector development, and post-fire
- Many of the design trades have identified a knowledge gap of what a spacecraft fire will look like
  - How large is it?, How rapidly does it grow?
  - Combustion products as a function of what is burning?
- A large-scale fire demonstration experiment is a logical “next step”
  - Material flammability, fire detection, and fire suppression are possible

3.0 Closure

Protecting spacecraft from fire has been of critical importance to NASA since the beginning of the human spaceflight program. During the design of new spacecraft, trade studies for fire detection, fire suppression, and post-fire cleanup and monitoring systems are conducted using the most recent knowledge regarding spacecraft fires. The design and implementation of these systems has evolved with succeeding vehicle as new data and hardware technologies have become available. Because of the specialized nature of fire protection in spacecraft operating in low- or partial-gravity, commercial off-the-shelf terrestrial fire safety technologies are seldom relevant. While current terrestrial fire safety technologies have developed over more than a century of fighting fires, spacecraft fire safety technology has only been studied for a little over 30 years with varying emphasis. The Fire Prevention, Detection, and Suppression technology development effort was the first concerted effort within NASA to advance spacecraft fire safety technologies and incorporate that technology into the design of crewed space vehicles and habitats. No matter what destination astronauts from the United States will eventually be directed, the implementation of a robust spacecraft fire safety technology development program between now and then will provide the best methods for them to respond to a fire, recover the vehicle, and continue with their mission. Crew safety has been and will continue to be the primary objective of NASA's spacecraft fire safety technology development effort.

4.0 Selected Bibliography

The major publications and presentations prepared by FPDS personnel from 2004 to 2010 are listed in this section. They are categorized into the topical areas of material flammability, fire detection, and fire suppression as well as several programmatic overview papers. Because technology development work in spacecraft fire safety will continue after the ETDP Fire Prevention, Detection, and Suppression project transitions to the ETDD program, this list of publications represents a "snap-shot" of the publications and will undoubtedly increase.

Programmatic

"Recommendations for Exploration Spacecraft Internal Atmospheres: The Final Report of the NASA Exploration Atmospheres Working Group," NASA/TP—2010-216134, October 2010.

Ruff, G.A., Brooker, J., and Urban, D.L., "Fire Safety Technology Development for Exploration Spacecraft and Habitats," Paper No. AIAA–2010–6240, 40th International Conference on Environmental Systems, Barcelona, Spain, July 11–15, 2010.

Ruff, G.A., "GRC's Fire Prevention, Detection, and Suppression Project," presented to the Director's Leadership Forum, NASA John H. Glenn Research Center, June 3, 2008.

Ruff, G.A., "GRC's Contributions to Fire Safety on Exploration Vehicles," presented to the Director's Leadership Forum, NASA John H. Glenn Research Center, December 1, 2006.

Material Flammability

Cavanaugh, J.M., Torvi, D.A., Gabriel, K.S., and Ruff, G.A., "Test Method for Evaluating Fabric Flammability and Predicted Skin Burn Injury in Microgravity," Microgravity Sci. Tech, Vol. XVIII-2, pp. 14–26, 2006.

Ferkul, P.V. and Olson, S.L., "Zero-Gravity Centrifuge Used for the Evaluation of Material Flammability in Lunar-Gravity," Paper No. AIAA–2010–6260, 40th International Conference on Environmental Systems, Barcelona, Spain, July 11–15, 2010.

Fereres, S., Lautenberger, C., Fernandez-Pello, C., Ruff, G.A., and Urban, D.L. "The Effect of Environmental Pressure on the Mechanisms Controlling the Piloted Ignition of Combustible Materials," Paper No. AIAA–2010–6261, 40th International Conference on Environmental Systems, Barcelona, Spain, July 11–15, 2010.

Hsu, S.-Y. and T'ien, J.S., "Flame spread over solids in buoyant and forced concurrent flows: model computation and comparison with experiments," Proceedings of the Combustion Institute, Vol. 33, in press.

Hsu, S.-Y. and T'ien, J.S., "Effect of Chemical Kinetics on Concurrent-flow Flame Spread over Solids: A Comparison Between Buoyant Flow and Forced Flow Cases," *Combustion Science and Technology*, 2010, accepted.

Hsu, S.-Y., Tseng, Y.-T., and T'ien, J.S., "Modeling Flame Spread and Extinction of Solids in Space Exploration Atmospheres," SAE Paper No. 2009-01-2492, 39th International Conference on Environmental Systems, Savannah, GA, July 12–16, 2009.

Hsu, S.-Y. and T'ien, J. S., "Pressure Extinction Limits of Non-premixed Flames," *Combustion Theory and Modeling*, Vol. 13, No. 5, pp. 885–900, 2009.

Hsu, S.-Y., *Flame Spread and Extinction Over Solids in Buoyant and Forced Concurrent Flows: Model Computations and Comparison With Experiments*, Ph.D. Dissertation, Case Western Reserve University, Department of Mechanical and Aerospace Engineering, May 2009.

Kleinhenz, J.E., *Flammability and Flame Spread of Nomex and Cellulose in Space Habitat Environments*, Ph.D. Dissertation, Case Western Reserve University, May 2006.

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McAllister, S., Fernandez-Pello, C., Urban, D.L., and Ruff, G.A., "The Combined Effect of Pressure and Oxygen Concentration on Piloted Ignition of a Solid Combustible," Combustion and Flame, Vol. 157, pp. No. 9, Sept. 2010, pp. 1753–1759.

McAllister, S., Fernandez-Pello, C., Ruff, G.A., and Urban, D.L., "Ignition Delay of Combustible Materials in Space Exploration Atmospheres," SAE Paper No. 2008-01-2088, 38th International Conference on Environmental Systems, San Francisco, CA, June 29-July 2, 2008.

McAllister, S., Fernandez-Pello, C., Ruff, G.A., and Urban, D.L., "Ignition Delay of Combustible Materials in Normoxic Equivalent Atmospheres," SAE Paper No. 2009-01-2491, 39th International Conference on Environmental Systems, Savannah, GA, July 12–16, 2009.

Miller, F.J., Olson, S.L., Gokoglu, S.A., and Ferkul, P.V., "Material Flammability Test Methods for Achieving Simulated Low-Gravity Conditions," Proceedings of the 5th U.S. Combustion Meeting, San Diego, CA, March 25–28, 2007.

Olson, S.L., Ruff, G.A., and Miller, F.J., "Microgravity Flame Spread in Exploration Atmospheres: Pressure, Oxygen, and Velocity Effects on Opposed and Concurrent Flame Spread," SAE Paper No. 2008-01-2055, 38th International Conference on Environmental Systems, San Francisco, CA, June 29-July 2, 2008 (also NASA/TM—2008-215260, August 2008).

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Olson, S.L. and Ruff, G.A. "Microgravity Flame Spread over Non-Charring Materials in Exploration Atmospheres: Pressure, Oxygen, and Velocity Effects on Concurrent Flame Spread, SAE Paper No. 2009-01-2489, 39th International Conference on Environmental Systems, Savannah, GA, July 12–16, 2009.

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14. ABSTRACT
The Fire Prevention, Detection, and Suppression (FPDS) project is a technology development effort within the Exploration Technology Development Program of the Exploration System Missions Directorate (ESMD) that addresses all aspects of fire safety aboard manned exploration systems. The overarching goal for work in the FPDS area is to develop technologies that will ensure crew health and safety on exploration missions by reducing the likelihood of a fire, or, if one does occur, minimizing the risk to the crew, mission, or system. This is accomplished by addressing the areas of (1) fire prevention and material flammability, (2) fire signatures and detection, and (3) fire suppression and response. This report describes the outcomes of this project from the formation of the Exploration Technology Development Program (ETDP) in October 2005 to September 31, 2010 when the Exploration Technology Development Program was replaced by the Enabling Technology Development and Demonstration Program. NASA's fire safety work will continue under this new program and will build upon the accomplishments described herein.

15. SUBJECT TERMS
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