THE SPACECRAFT FIRE EXPERIMENT (SAFFIRE) - OBJECTIVES, DEVELOPMENT AND STATUS

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ABSTRACT

Since 2012, the Spacecraft Fire Experiment (*Saffire*) has been under development by the Spacecraft Fire Safety Demonstration (SFS Demo) project that is funded by NASA's Advanced Exploration Systems Division in the Human Exploration and Operations Mission Directorate. The overall objective of this project is to reduce the uncertainty and risk associated with the design of spacecraft fire safety systems for NASA's exploration missions. This is accomplished by defining, developing, and conducting experiments that address gaps in spacecraft fire safety knowledge and capabilities identified by NASA's Fire Safety System Maturation Team. This paper describes the three Spacecraft Fire Experiments (Saffire-I, -II, and -III) that were developed at NASA-GRC and that will conduct a series of material flammability tests in low-gravity and at length scales that are realistic for a spacecraft fire. The experiments will be conducted in Orbital ATK's Cygnus vehicle after it has unberthed from the International Space Station. The tests will be fully automated with the data downlinked at the conclusion of the test and before the Cygnus vehicle reenters the atmosphere. The objectives of these experiments are to (1) determine how rapidly a large scale fire grows in low-gravity and (2) investigate the low-g flammability limits compared to those obtained in NASA's normal gravity material flammability screening test. The hardware for these experiments has been completed and is awaiting their respective launches, all planned for 2016. This paper will review the objectives of these experiments and how they address several of the knowledge gaps for NASA's exploration missions. The hardware development will be discussed including several novel approaches that were taken for testing and evaluation of these series payloads. The status of the missions and operational status will also be presented.

1. INTRODUCTION

Tests on full-scale transportation vehicles, buildings, homes, and habitats have been common on earth to more fully understand the fire hazards associated with each application and how best to protect the passengers and inhabitants from a potential fire. Fire safety on spacecraft has been a significant concern for NASA during the decades of crewed spaceflight and will remain so as NASA plans future exploration missions. Many microgravity combustion experiments have been performed on the Space Shuttle and continue to be performed on the International Space States (ISS) and the data from these experiments have contributed to our understanding of how to prevent and protect crewed spacecraft from fire. However, none of these experiments have studied sample and environment sizes typical of those expected in a spacecraft fire [1]. Prior experiments have been limited to samples no larger than 10 cm in length and width whereas a serious spacecraft fire would likely be much larger and consume much more material. Because of the large differences between fire behavior in normal and reduced gravity, there is a significant lack of data available for spacecraft designers on which to base their fire safety designs and procedures. The use of terrestrial fires and fire standards to design spacecraft fire safety systems presents an inherent risk to the vehicle because of the significant level of uncertainty. While this approach has been successful thus far, the uncertainty and risk will increase as exploration missions venture further from earth with considerably longer transit times for a safe return. Despite their obvious importance, full scale spacecraft fire experiments have not been possible because of the inherent hazards involved with conducting a large fire test in a crewed vehicle. To address this knowledge gap, a project was proposed to conduct large-scale fire safety experiments in an expendable spacecraft without risk to a crew.

In October 2011, the NASA Advanced Exploration Systems (AES) Division of NASA's Human Exploration and Operations Mission Directorate funded this project to develop and demonstrate spacecraft fire safety technologies in relevant environments. The keystone demonstration to be performed was a large-scale fire safety experiment to be conducted on an ISS re-supply vehicle after it has left the ISS and before it enters the earth's atmosphere. The project team led from NASA's John H. Glenn Research Center (GRC) was identified and began formulating such an experiment. The NASA team was augmented by an international topical team assembled by the European Space Agency (ESA) [2]. The participation of members from other countries and space agencies not only brings additional skills to the science team but also facilitates international cooperation in the development of an approach to spacecraft fire prevention and response for future exploration vehicles. The current spaceflight experiment funded and being developed by NASA addresses two objectives. The first objective is to understand the flame spread and growth of a fire over a large piece of flammable material, consistent with clothing or other fabric likely to be in a spacecraft cabin. This sample material is approximately 0.94 meters long and 0.4 meters wide. This will be at least an order of magnitude larger in both dimensions than any prior low-g flame spread experiment. The second objective is to examine the flammability limits of materials in low gravity for comparison with results of NASA's terrestrial normal gravity evaluation tests. The status of the development of the flight experiment and the individual contributions of the topical team will be discussed in subsequent sections.

2. EXPERIMENT DESCRIPTION

The premise for the design of the flight experiment was that practically all of the hardware would be identical in the three units except possibly for the sample material(s) to be burned. The concept for this experiment focuses on conducting two types of material combustion tests to be performed on different flights of the *Cygnus* vehicle. The experiment package consists of a flow duct and an adjacent avionics bay. A schematic of the flow duct is shown in Fig. 1. The flow duct forms the primary chamber of the experiment while the avionics bay is connected to the side of the flow duct as shown in the figure. A Lexan^{TM} panel forms the wall between the flow duct and the avionics bay. Air is drawn through the flow duct by fans located at the top of the duct with flow straighteners at the bottom of the experiment module. The flow duct/avionics bay assembly is a rigid structure and will be secured with the standard stowage straps used in the *Cygnus* vehicle. This duct will provide a uniform flow across the samples, maintain a clear flow path within the experiment module, and prevent burning debris from interacting with the rest of the cargo. The sample card is positioned in the center of the flow duct as shown in Fig. 1.

2.1 Sample Materials

The sample material for Saffire-I and III is a composite fabric consisting of cotton on a fiberglass substrate (75% cotton, 25% fiberglass by weight). It is called SIBAL cloth because it was developed for the Solid Inflammability Boundary at Low-Speeds (SIBAL) spaceflight experiment and has been used in many space experiments because it burns like cotton but maintains structural integrity after the cotton is consumed. The objective of the Saffire-I and III tests will be to determine how rapidly a large-scale fire grows in low-gravity and whether it reaches a steady-state spread rate. Saffire-I will be conducted at an air flow velocity of 20 cm/s while Saffire-III will be run at a flow velocity of 30 cm/s .

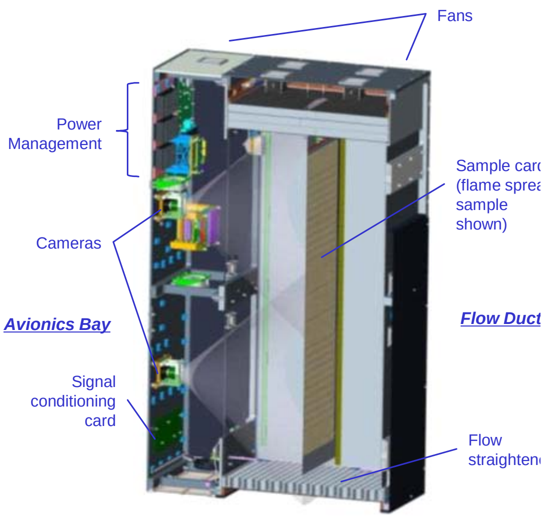

Figure 1: Schematic of the Spacecraft Fire Safety Demonstration Experiment. *The experiment module consists of a flow duct containing the sample card and an avionics bay. All power, computer, and data acquisition modules are contained in the bay. The experiment module is approximately 53- by 90- by 133-cm.*

Saffire-II has a sample card that contains 9 samples, each 5 cm x 29 cm. Table 1 lists the samples contained on Saffire-II while Fig. 2 shows their locations on the sample card. These materials were selected because they have normal gravity Maximum Oxygen Concentration (MOC) flammability limits that indicate they will burn in normal gravity just above and below 21% O_2 by volume, *i.e.*, the expected concentration of O_2 when

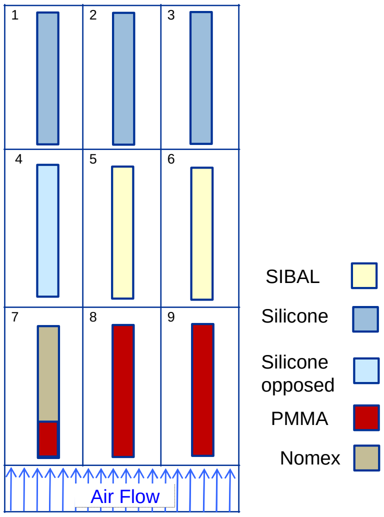

Figure 2: Sample layout for Saffire-II

Table 1. Saffire-II Samples

Sample Number	Material	Sample Thickness	Air Flow (cm/s)	Igniter Position
S1	Silicone	0.25 mm	20	Upstream
S2	Silicone	0.61 mm	20	Upstream
S3	Silicone	1.02 mm	20	Upstream
S4	Silicone	0.36 mm	20	Downstream
S5	SIBAL fabric	0.33 mm	20	Upstream
S6	SIBAL fabric	0.33 mm	30	Upstream
S7	PMMA to Nomex	0.33 mm	20	Upstream
S8	Structured PMMA	10 mm (with tapered edge for ignition)	20	Upstream
S9	Flat PMMA	10 mm (with tapered edge for ignition)	30	Upstream

Cygnus unberths from ISS. Drop tower testing has demonstrated the MOC flammability limits of a material can be different in low-g than in normal gravity [3-5]. Therefore, the objective of the Saffire-II tests is to quantify that affect in long-duration low-gravity using samples of the same size as those used in the in NASA-STD-6001 Test 1 normal-gravity tests [3]. Some of these samples are expected to burn while others may not.

Quantifying the difference in flammability limits for large samples is the objective of the Saffire-II experiments.

Table 2. Saffire-I, II, and III Diagnostics

Measurement	Method	Location
Flow temperature	thermocouples	inlet and outlet of flow duct
Flame temperature	thermocouples	embedded in sample
Plume temperature	thermoocouple	
Flame radiation	radiometers	two viewing front of sample; two viewing back of sample
CO_2 mole fraction	solid-state sensor	in avionics bay
O_2 mole fraction	solid-state sensor	inlet to avionics bay
Pressure	solid-state sensor	in avionics bay
Flow velocity	anemometers	one on each side of sample
Flame image	cameras	two viewing front of sample
Flow uniformity	smoke wire	leading edge of sample

2.2 Diagnostics

Camera images of the flame are the primary data measurement obtained from the Saffire experiment but there are other diagnostics to measure other flow, flame, and atmospheric parameters. The diagnostic suite used in Saffire are shown in Table 2. The primary experiment data will be provided by two cameras that view one side of the sample card.

2.3 Experiment Development

The Saffire flight systems (hardware and software) underwent the NASA flight experiment development reviews and testing although these processes were heavily tailored to realize savings in cost and schedule. Because all three units were being developed in parallel, some components were ready to progress to the next development phase before the entire system for all three units had completed that phase. The logic behind the tailoring was to tailor the review criteria to allow components that were ready to progress onto the next development phase while the remainder of the system was completed. Given the design of the system and the risk tolerance advocated by the Advanced Exploration Systems Division, this approach was warranted. A Mission Concept Review/System Requirements Review was held in November 2012 and followed approximately 7 months later by a Periodic Technical Review-1 (PTR-1) that combined NASA's typical Preliminary Design Review/Critical Design Review.

Fabrication of the mechanical components for Saffire-I was performed at NASA-GRC to ensure the accuracy of the drawings. NASA's Fabrication Alliance, a coordination of the fabrication shops at all NASA centers, was used to manufacture some of the components for Saffire-II and III again to help maintain project schedule without being limited by the staffing demands of other projects at NASA-GRC. Components for the second and third flight units was performed by the Fabrication Shops at NASA Johnson Space Center (JSC) and White Sands Test Facility (WSTF). All avionics manufacturing was conducted at NASA-GRC.

Periodic Technical Review-2, a tailored System Integration Review marking the start of system assembly was held in February 2014 with the assembly of the flight system being completed in October 2014. Because of the similarity of the slight systems and the risk posture of AES projects, the project tailored the approach to environmental testing and functional testing. Table 3 shows the environmental tests performed on each flight unit along with the date this testing began.

Various levels of functional testing was performed on all three flight units before and after all environmental testing to verify the health of the flight unit being tested and to collect performance data. Additional functional testing was performed throughout 2015 for validation and verification of software and other systems. These test results were compared across all three flight units to

Table 3. Summary of Saffire Environmental Tests

Test	Saffire Unit/Date		
	I	II	III
Safety-critical Relay Component Vibe Test	Nov-13	Nov-13	Nov-13
Camera Component Vibe Test	Dec-13	Dec-13	Dec-13
Power Management System Vibe Test	--	Mar-14	Mar-14
System Vibe Test	Oct-14	--	--
System Thermal Test	Nov-14	Oct-14	Nov-14
Off-gas System Test	--	Nov-14 (samples only)	Nov-14
EMI/EMC System Test	Dec-14	Jan-15	Feb-15

verify and demonstrate consistency between the flight units. The System Acceptance Review marking the completion of the flight hardware was held in September 2015.

2.4 Launch and Operation

The Saffire-I flight unit was successfully launched within the Cygnus PCM on an Atlas V launch vehicle on March 22, 2016 as part of the OA-6 mission. The Cygnus vehicle was successfully berthed to the ISS on March 26, 2016. As of the writing of this paper, the un-berthing of the Cygnus is scheduled for June 2, 2016 and Saffire-I is scheduled to operate a few hours afterwards. Data from Saffire-I will be downlinked over the next several days prior to destructive re-entry of Cygnus about June 10. Saffire-II and III are planned to launch from the Wallops Flight Facility on Orbital ATK's Antares rocket with the tentative dates shown in Table 4.

Table 4. Launch and Operation Dates for Saffire-I-III (as of 4/30/2016)

	Mission	Launch	Operations
Saffire-I	OA-6	22-Mar-2016	2-Jun-2016
Saffire-II	OA-5	NET 6-July-2016	19-Sep-2016
Saffire-III	OA-7	30-Dec-2016	3-Mar-2017

NET - no earlier than

3. SAFFIRE EXPERIMENT SAFETY

Even though this experiment will be conducted during the un-crewed portion of the flight, the Cygnus vehicle berths with the ISS and, therefore, the experiment is subject to many of the same safety considerations as other ISS payloads. The major safety hazard is inadvertent igniter activation prior to the Cygnus de-berthing from the ISS. This would result in the exposure of the flight crew to toxic gases that are produced from the combustion event. It should be noted that this hazard is a concern prior to Cygnus berthing to the ISS since the toxic gases would be present when the Cygnus hatch is opened to the ISS. The power and communication interfaces between Cygnus and Saffire are utilized to control this hazard. Cygnus provides two power feed circuits to Saffire due to power requirements. One power feed circuit provides power to the Saffire avionics, the other provides power to the igniter circuitry. There are two latching relays in each of these two power feed circuits, one in the power feed side, one in the return. These four latching relays are contained within the Saffire flight unit but are controlled and monitored by Cygnus avionics. A separate ground command to the Cygnus avionics is required to close each of these four latching relays. Igniter activation requires that all four relays be closed. This is because Saffire avionics provides an enable command to a DC/DC converter in the igniter circuitry and also provides commanding to solid state relay switches on the igniter control card within the igniter power feed circuitry. In addition, a ground command to the Saffire avionics via Cygnus avionics is required to initiate an igniter activation for an experiment run. Cygnus avionics and the associated ground commanding provide the required failure tolerance for control of the Saffire hazard of inadvertent igniter activation.

Significant focus was placed on these four latching relays due to their safety criticality. This attention is reflected in the environmental testing performed as shown in Table 3. The relays for all three flight units were vibration tested at the component level. Tailoring of the environmental testing resulted in only Saffire I being vibration tested at a system level. Therefore, vibration testing was performed on the Saffire II and III Power Management Systems that includes the relays to address the criticality of these relays and the associated risk of this tailored system-level vibration testing. Safety engineering input was critical to developing a design solution that was acceptable from an ISS payload safety perspective due to the interface limitations between Saffire and Cygnus.

This hazard along with the other typical ISS payloads hazards are documented in the Saffire Unit I Flight Safety Data Package. The ISS Payload Safety Review Panel (PSRP) reviewed and approved this Package at the Phase I/II level in August of 2013 and again at the Phase III level in March 2015. These Payload Safety Reviews were augmented by a handful of Technical Interchange Meetings (TIMs) with the PSRP including TIMs to address the inadvertent igniter activation hazard. These TIMs were of tremendous value in the overall safety approval process by providing a focused review of specific safety issues.

Table 5. Spacecraft Fire Safety Demonstration Experiment Objectives

Area	Objective	Comment	Saffire-I, II, III	Saffire-IV, V, VI	Ground
Fire behavior/modeling:	Quantify growth and end state of realistic fires in spacecraft and their influence on vehicle habitability	Require to validate computational models	X	X	
Fire growth/dynamics	Flame behavior in complex geometries	More realistic configurations than Saffire-I, II, and III		X	
	Flame behavior for planar and complex geometries in exploration atmospheres	Elevated O_2, lower P; compare with Saffire-I, II, III; supplement small-scale tests in Combustion Integrated Rack		X	
	Measure flame behavior over large-scale planar surfaces	Continues Saffire-I and III investigations	X	X	
Post-fire monitoring	Demonstrate performance of prototype Orion and ISS combustion product monitor	Demonstration of prototype flight hardware		X	X
Fire Detection	Obtain data to validate transport and detection models	Required for model development		X	X
	Demonstrate fire detection with multi-moment sensors	Demonstrate capability to reject nuisance alarms			X
	Evaluate performance of hybrid fire detection (smoke and gaseous products)	Combustion product detection by prototype combustion product monitor			X
Post-fire monitoring	Quantify rate of decay of gas species after a spacecraft fire	Required for model development		X	X
Post-fire cleanup	Quantify atmosphere cleanup rate with prototype smoke-eater	Demo of prototype flight hardware		X	X
Fire Suppression	Performance of low-momentum water mist suppression	Effectiveness of fire ports using water mist fire suppression			X

4. SPACECRAFT FIRE SAFETY KNOWLEDGE GAPS AND FUTURE EXPERIMENTS

The experiments being developed for Saffire-I, -II, and –III will be the first of their kind to evaluate low-g material flammability with direct implications for fire safety on future exploration vehicles. One of the drawbacks of these experiments is that a relatively small number of tests will be conducted (two large samples and nine smaller samples). A thorough evaluation of these phenomena would require many more samples and range of materials. Also, if they are typical of most low-g combustion experiments, the findings will raise additional significant questions for material flammability in spacecraft. The Saffire hardware and the Cygnus vehicle provides a unique opportunity to demonstrate other fire safety technologies including fire detection, fire suppression, post-fire cleanup and monitoring. Needs in these areas have been identified by NASA's Spacecraft Fire Safety Systems Maturation Team and are summarized in Table 5. Because of the importance of addressing these remaining needs to crew safety in exploration missions, AES management authorized the SFS Demo project to plan for three more Saffire experiments, Saffire-IV, V, and VI, that will address objectives not achieved in Saffire-I-III. Of particular note is that many of these objectives require supporting ground-based experimentation to perform the parametric investigations that are required to fully understand the phenomena in question. The objective of the flight experiment is to anchor the ground-based experiments with flight data.

While the planning for the follow-on experiments is underway, the development process is intended to mirror the processes executed with Saffire-I-III. The Mission Concept Review/System Requirements Review is planned for June 2016 with a design review planned for December 2016.

5. CONCLUSIONS

The Spacecraft Fire Safety Demonstration Project has designed, manufactured, assembled and tested three Saffire flight units. The decision to develop flight units of nearly identical design allowed for the tailoring of environmentally testing that resulted in cost and schedule savings without introducing significant risk. This design similarity also allowed for the comparison of test results to verify consistency when testing was performed across all three flight units. Safety engineering input was critical to developing an acceptable design solution to control the inadvertent igniter activation hazard due to the interface limitations between Saffire and Cygnus. Technical Interchange Meetings (TIMs) with the ISS Payload Safety Review Panel proved to be invaluable to the overall safety approval process by providing a focused review of specific safety issues.

Conducting these three experiments will be a milestone for spacecraft fire safety. The data and follow on analysis will provide verification of spacecraft fire safety design and operations for future exploration vehicles and their crews. Development of the Saffire-IV – VI flight units will extend spacecraft fire safety knowledge related to the combustion by-products and fire detection.

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