Operation and Development Status of the Spacecraft Fire Experiments (*Saffire*)

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Since 2012, a series of Spacecraft Fire Experiments (Saffire) have been under development by the Spacecraft Fire Safety Demonstration (SFS Demo) project, funded by NASA's Advanced Exploration Systems Division. 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. The approach to achieving this goal has been to define, develop, and conduct experiments that address gaps in spacecraft fire safety knowledge and capabilities identified by NASA's Fire Safety System Maturation Team. The Spacecraft Fire Experiments (Saffire-I, -II, and -III) are material flammability tests at length scales that are realistic for a spacecraft fire in low-gravity. The specific objectives of these three 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 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 before the Cygnus vehicle reenters the atmosphere. This paper discusses the status of the Saffire-I, II, and III experiments followed by a review of the fire safety technology gaps that are driving the development of objectives for the next series of experiments, Saffire-IV, V, and VI.

Nomenclature

AES	=	Advanced Exploration Systems
ATV	=	Automated Transfer Vehicle
CO	=	Carbon Monoxide
CO_2	=	Carbon Dioxide
ESA	=	European Space Agency
FOT	=	Flight Operations Team
GRC	=	John. H. Glenn Research Center
HCl	=	hydrogen chloride
HF	=	hydrogen fluoride
HTV	=	H-II Transfer Vehicle
ISS	=	International Space Station
JAXA	=	Japan Aerospace Exploration Agency
LED	=	Light-emitting diode
MOPS	=	Mission Operations Team
TRL	=	Technology Readiness Level

I. 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). 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

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environment sizes typical of more serious fires aboard a spacecraft.[1] Prior experiments have been limited to samples no larger than 10 cm in length and width whereas a serious spacecraft fire could consume as much as an order of magnitude 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 only 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 spacecraft. To address this knowledge gap, the Spacecraft Fire Safety Demonstration (SFS Demo) 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 stated keystone demonstration was a large-scale fire safety experiment to be conducted on an International Space Station (ISS) re-supply vehicle after it has undocked from the ISS and before it enters the atmosphere. The project team led from NASA 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). Each member of this team brings expertise and funding from their respective space and research agencies for their activities. 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. No single experiment can address the range of issues that need to be resolved to fully understand the fire risk to future spacecraft and missions. The goal of the topical team is to leverage the international capabilities of each team member to develop a suite of ground-based and space flight spacecraft fire safety experiments that will expand the impact of the flight experiments. 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 an amount of flammable material consistent with what is likely to be in a spacecraft cabin. This sample material (Saffire-I and III) is approximately 0.94 meters long and 0.4 meters wide. As previously stated, 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 *(Saffire-II)*. The status of the development of the flight experiment and the individual contributions of the topical team will be discussed in subsequent sections.

II. Background and Status

The unique objectives of this experiment necessitated the use of an expendable ISS resupply vehicle such as ESA's ATV, JAXA's HTV, Orbital ATK's Cygnus or SpaceX's Dragon. Soon after the initiation of this project, the European Space Agency (ESA) became interested in this experiment and the opportunities for additional collaboration with NASA. As a result, an experiment concept was initially developed to fly in an ATV vehicle. Dr. Olivier Minster, Senior Physical Scientist in the Directorate of Human Spaceflight for the European Space Agency formed an international topical team chaired by Professor Grunde Jomaas (Technical University of Denmark) and Professor Jose L. Torero (University of Queensland, Brisbane, Australia.). This "Fire Safety in Space" International Topical Team has grown to consist of 15 researchers from the European, Japanese, Russian, and U.S. spacecraft fire safety communities and is tasked to define research that would be possible from such a low-gravity fire safety experiment. The group developed the initial science and technology requirements for this experiment as well as ground-based experiments and modeling efforts that support this experimental campaign.

While many factors would go into the selection of a vehicle such as available volume, power, communication, *etc.*, the schedule and required financial resources eventually became the most significant. With the planned ATV flights ending with ATV-5 in March 2014 (flown in July 2014), it became unlikely that an experiment could be developed and integrated into the vehicle within the time allotted. Since Orbital ATK had planned eight Cygnus flights to begin in 2013 and extending into 2016 (now 2017), the use of the Cygnus vehicle was more promising for the successful completion of this experiment. Programmatic requirements and fire safety technology needs later drove the project to plan for three experiments to be performed on three consecutive flights of Cygnus. Even though the ESA ATV-5 vehicle was no longer being considered for this experiment, the international topical team remained intact and functioning to help formulate the experiment and associated ground-based research.

III. Saffire Experiment

A. Hardware

One of the most significant aspects of the design of the Saffire-I, II, and III flight experiments was that the hardware would be as close to identical as possible between the three units except possibly for the sample material(s) to be burned. The experiment package consists of a flow duct and an adjacent avionics bay as shown in the schematic 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™ panel forms the wall between the flow duct and the avionics bay to allow imaging of the front of the sample by two cameras located in 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 differences between the units is in the sample card and samples to be burned as will be discussed in Section III.C.

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.*

B. Diagnostics

The experiment package will have a range of diagnostics to monitor the test conditions. The ambient temperature will be measured at the inlet of the flow duct, in the flame plume, and at the outlet of the duct just upstream of the fans. The oxygen and CO_2 concentrations will be measured at the inlet of the avionics bay so that the sensors do not degrade the flow uniformity in the flow duct. A pressure transducer will also measure the pressure time-history. Two flow anemometers, one on each side of the sample will quantify the flow velocity in the duct and serve as input to the fan flow control algorithm. Two video cameras located in the avionics bay will provide front views of one side of the entire sample through a Lexan™ panel separating the flow duct from the avionics bay. The sample will also be periodically illuminated by a green LED source to allow the measurement of the pyrolysis length. Four calibrated radiometers, two viewing the front of the sample and two viewing the back, will measure the broadband radiative emission from the sample to provide an estimate of the radiative flux from the burning zone towards the surroundings. The flame stand-off distance is an important characteristic for comparing the data with computational models and will be measured for the larger flame spread samples using several thermocouples placed at varying heights above the sample surface. The thermocouple wires are woven into the sample and then bent upward so they are perpendicular to the surface.

C. Saffire-I, II, and III Samples

The objective of the Saffire-I experiment is to investigate flame spread and growth in low-gravity. Specifically, the experiment will determine if there is a limiting flame size when burning over a large surface and quantify the size and growth rate of the flames. The flame will propagate over a panel of thin material approximately 0.4 m wide by 0.94 m long as shown in Fig. 2a. A wire igniter is woven into the fabric along the upstream edge and will be energized to ignite the sample. This material will be expected to burn at the anticipated oxygen mole fraction of the cabin atmosphere (near 0.21 O_2 mole fraction). A second redundant igniter is woven into the fabric at the downstream end of the sample in case of a failure of the upstream igniter or if the flame does not propagate the entire length of the sample. The objective of the tests to be conducted on Saffire-II is to investigate the low-gravity Maximum Oxygen Concentration (MOC) flammability limits in long-term low gravity.[2] The configuration for these experiments consists of nine samples of varying materials (denoted flammability samples) each having dimensions of approximately 5 cm wide by 29 cm long installed on the same panel in place of the single sample in Fig. 1. The Saffire-II sample card is shown in Fig. 2b. These samples emulate the configuration used in NASA-STD-6001 Test 1.[3] Each sample is ignited at the bottom using a hot wire. The oxygen concentration in the Cygnus vehicle will be nearly 21% by volume—the same as in the ISS when the hatch was closed. The materials have been selected to be near their normal-gravity or hypothesized low-gravity maximum oxygen concentration in 21% O_2. This has complicated the selection of sample materials because most materials relevant for spacecraft do not have normal-gravity flammability limits near 21% oxygen by volume.[4-6] Camera images are the primary diagnostics for these tests as the intended result is primarily to determine whether the flame propagates or self-extinguishes. If it propagates, additional data such as flame spread rate will be obtained.

a. Saffire-I and -III sample card. *The sample is a composite fabric (75% cotton – 25% fiberglass by mass) and is0.4 m wide x 0.95 m long.*

b. Saffire-II sample card. *Card contains nine samples (5 cm x 29 cm) of PMMA (flat and structured) Silicone (3 thicknesses, different ignition direction), composite fabric from Saffire-I, III, and Nomex (with PMMA ignition)*

Figure 2. Sample cards for the Saffire-I, II, and III experiments.

D. Experiment Development

As a spaceflight experiment, Saffire has undergone the typical suite of programmatic and design reviews during its life cycle. However, to meet the schedule imposed by AES, the reviews were heavily tailored with several reviews being combined. NASA's milestone reviews are planned to assess hardware and software readiness before moving into the next phase of development, *i.e.,* a System Requirements Review is the gate between requirements development and the design phase; a Critical Design Review is the gate between the design phase and manufacturing. The philosophy behind the timing and content all the reviews in the Spacecraft Fire Safety Demonstration Project was to demonstrate the required readiness but push the hardware into the next phase of development as rapidly as possible, thereby shortening the overall development cycle. With three flight systems and their numerous sub-systems being simultaneously fabricated, assembled, and tested, this philosophy was essential for maintaining project cost and schedule. The System Acceptance Review, the major review that verifies completion of the flight system was held in September 2015.

E. Flight Status and Operations Summary

The Saffire-I flight unit was integrated into the Cygnus PCM on January 25, 2016 with several pictures of the installation shown in Figure 3. The hardware remained in Cygnus through the preparations for the launch of OA-6. The Saffire-I hardware was successfully launched into orbit on March 22, 2016 aboard an Atlas-V from Cape Canaveral. Cygnus berthed with ISS on March 25 and is scheduled to remain there until June 14 (as of May 5). Saffire power is inhibited (relays open) during launch, rendezvous, berthed operations, and departure from ISS. After Cygnus has unberthed from ISS and concluded joint operations, Saffire-I operations will begin.

All commanding of and communication with the Saffire payload is performed by the Orbital ATK Mission Operations Team (MOPS) from the Orbital ATK Mission Control Center in Dulles, VA. Payload and vehicle telemetry will be received in real time by MOPS, viewed by the Saffire Flight Operations Team (FOT) stationed at MCC-D (FOT-Console and FOT-Backup) and then transferred to a drop box where it will be picked up by FOT members at NASA-GRC (FOT-GRC). This telemetry includes vehicle and Saffire data such as radiometer and anemometer output, fan tachometer readings, and voltage and current histories from the smoke wire and upstream and downstream igniters. These data, along with the state of the four relays powering Saffire, will be available during all experiment phases.

Operations on the day of Cygnus unberthing will include closing the two relays that power the avionics and sending time-sync and initialization commands that run a built-in test (BIT) of the Saffire system. Pending successful outcomes of these tests, the igniter relays will be closed and the RUN command will be issued to begin the experiment. The Saffire-I experiment will be complete within about 30 minutes and the on-board computer will begin the process of compressing the images for data download. Image compression will take approximately 1.5 hours to complete during which time the Mission Support Team at NASA-GRC will review the telemetry data to determine which one of three pre-specified downlink commands will be issued. These commands are prepared to downlink compressed images of the first three minutes of the burn from the upstream igniter (nominal), the burn from the downstream igniter, or a combination of both. This command will be issued in the afternoon of the day of Cygnus unberthing with the data files downlinked during the ground passes occurring that night. On the morning of day 2, the Mission Support Team should have the initial images to review. Operations for days 2-8 will consist of identifying the specific raw images (i.e., uncompressed) to be downlinked, preparing the commands to downlink this data, and preparing and issuing commands to downlink data packets that were requested but not received. Of course, the raw images have a higher resolution that the compressed images and will be used for the majority of the science analysis. By contract, Cygnus will remain in orbit for up to 8 days to downlink data or until 20 Gbits (2.5 Gbytes) of data are received. When data downlink is completed, the relays that power the Saffire avionics will be opened, officially ending the Saffire-I experiment.

Following the experiment, detailed analysis of the results will commence by researchers at NASA GRC and the "Fire Safety in Space" International Topical Team that has assisted in defining the Saffire experiments. Based on the the current schedule, Saffire-II will be integrated into the OA-5 Cygnus PCM on May 12, 2016. The Saffire-II launch is planned for no earlier than July 6 with operations occurring in September 2016.

a. Saffire-I hardware installed in the Cygnus OA-6 PCM. *Saffire was the first cargo loaded and will be followed by the loading of cargo on each of the four pallets (front, back, starboard, and aft).*

b. Close-up of the Saffire-I hardware installed in the Cygnus OA-6 PCM. *Sheets of white Zytec foam is placed between the hardware and the black straps. The inlet and outlet of the Saffire flow duct is on the ends and do not have foam.*

Figure 3: The Saffire-I hardware installed in the Cygnus OA-6 Pressurized Cargo Module (PCM).

IV. Spacecraft Fire Safety Technology Needs for Exploration

From the outset, the objective of the Spacecraft Fire Safety Demonstration project was to address technology and knowledge gaps related to fire safety. These gaps were identified by the Spacecraft Fire Safety Systems Maturation Team (SMT) in 2013 and are shown in Table 1. They have remained relatively unchanged since then as the SFS Demo project and other activities continue to address them. What is lacking in the verification of these technologies is a large scale demonstration of fire response in a spacecraft that makes use of these . This was recognized by AES and in 2014 they requested that the SFS Demo project develop three more Saffire experiments that will not only continue to investigate large-scale fires in long-duration low-gravity but also draw on the on-going ground-based work to demonstrate technologies for fire detection, monitoring, and cleanup.

Table 1. Spacecraft Fire Safety Technology Gaps for Exploration Missions

Technical Area	Tech Goal addressed	Gap
Low- and partial-gravity Material Flammability	Accurate definition of the risk from material flammability in low-g (identify material flammability limits in low-g environment)	• Quantification of risk from NASA-STD- 6001 Test 1 normal-g data • Growth rate of fire hazard
Fire Detection	Common fire detectors for exploration. Early fire detection from structurally integrated distributed sensors	• Particle size discrimination • Adaptation of state-of-art technology
Fire Suppression	ECLS-compatible and re-chargeable fire extinguisher	• Scaling to vehicle • Size of critical fire
Emergency Crew Mask	Emergency breathing apparatus with filtering respirator	• Flame resistant • One size fits all • Can be donned in 5 sec • Resists chemical breakthrough
Post-fire (combustion product) monitoring	Contingency air monitor for relevant chemical markers of post-fire cleanup	• Measurement of CO, CO_2, HF, HCl, HCN • Battery-operated • Hand-held • Calibration duration 1-5 years
Post-fire/leak Clean-up	Contingency air purifier for post-fire and leak cleanup	• Stand-alone • Low (integrated) power, low mass/volume
Fire Scenario Modeling and Analysis	Definition of a realistic spacecraft fire to size	• Validated models of impact of a large scale fire on the spacecraft volume and cabin conditions • Analysis to size fire suppression and cleanup equipment based on vehicle parameters

Of course, making the jump from technologies and performance gaps to a well-defined experiment that effectively demonstrates these technologies requires considerable effort. Researchers and technologists in the SFS Demo project as well as the Fire Safety in Space international topical team have developed objectives that would be conducted in a Saffire-IV, V, and VI series of flights and that address these gaps. This series of flights will make use of not only the Saffire flow chamber to burn samples but also the Cygnus vehicle itself to obtain data on how the heat, smoke, and gaseous combustion products interact with the spacecraft volume. The list of experiment objectives for Saffire-IV-VI are shown in Table 2 in the order of priority based on deliberations of the Spacecraft Fire Safety SMT. Also shown in this table are the investigations that will address these objectives. There are several significant factors illustrated in this table. First, all of these objectives require a demonstration to anchor the technology in the environment of use, *i.e.*, long-duration low-gravity on a vehicle scale. Several of these gaps are addressed on Saffire-I-III but others will require implementation on Saffire-IV-VI. Also, many require a more intensive parametric study that can only be achieved through a supporting ground-based investigation.

One interesting aspect of the objectives shown in Table 2 is that the fire behavior and modeling objective is a primary objective – emphasizing the need to obtain data that can be used to extrapolate results to the different vehicles and habitats required to perform NASA’s exploration missions. Another observation is the priority placed on material flammability in exploration atmospheres – *e.g.* in ambient conditions having oxygen mole fractions up to 0.34 and pressures of 8.2 psia. These conditions bound those considered for exploration missions. While elevated oxygen and reduced pressure conditions are generally considered for planetary or asteroid operations where frequent extravehicular activities (EVA) are required, the Cygnus environment provides the unique opportunity to explore these conditions at relevant scales and obtain data that can anchor computational models that will be applied during analysis of fire scenarios.

Table 2. 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 CIR		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 CPM	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

For fire detection, the size of smoke particulate produced in low-gravity has been investigated by the Smoke Aerosol Measurement Experiment (SAME)[7,8]. Transport models of smoke and combustion products have been developed based on these results but the models themselves have not been validated. The Saffire-IV-VI experiments in a Cygnus vehicle provide the unique opportunity to obtain this data. Similarly, the transport and detection of gaseous combustion products, especially acid gases like hydrogen fluoride (HF) and hydrogen chloride (HCl) that have a propensity to attach to smoke particulate and other surfaces must be quantified to define fire response protocol. Additionally, the demonstration of a post-fire monitoring technology for these chemical species will significantly advance the technology readiness level (TRL) of this instrument and bring it closer to implementation both on ISS, Orion, and future exploration vehicles.

Obtaining data on the ability of advanced sorbents to remove carbon monoxide (CO) from the atmosphere in a spacecraft environment will aid spacecraft environmental control and life support (ECLS) designers to develop systems that can rapidly clean-up the cabin atmosphere following a fire event. The Cygnus vehicle provides a unique environment to demonstrate this technology and provide data essential for the design of clean-up systems for exploration vehicles and habitats.

The ground tests in post fire monitoring and cleanup indicated in Table 2 are planned for a Spacecraft Flow Simulator Facility being constructed at NASA-GRC. This facility will be similar to the geometric and volumetric configuration of the Cygnus vehicle with the ability to include advanced diagnostics to characterize particulate and gaseous combustion product transport in a relevant environment. It will also be used to test various ground development units developed for Saffire-IV-VI.

One technology for which additional low-g validation is currently not planned is fire suppression using fine water mist extinguisher. Forced convection is the primary driver when a water mist extinguisher is activated making ground demonstrations highly effective in validating its performance. Also, determining the minimum amount of suppression agent required to extinguish a fire requires multiple tests to obtain statistically significant results and, therefore, is not conducive to the limited demonstration opportunities in the Saffire-IV-VI experiments.

Concepts for the Saffire-IV-VI hardware are being developed along with the set of engineering requirements that encompass science, safety, and vehicle requirements. A Mission Concept Review/System Requirements Review is planned for June 2016 with the designs being completed later in 2016. Flight hardware availability for Saffire-IV is currently planned for Fall 2018.

V. Conclusion

The Saffire series of experiment provides the unique opportunity to address gaps in knowledge and capabilities regarding fire safety aboard spacecraft. The Saffire-I, II, and III flight systems will address large-scale flame spread and material flammability limits, both essential components of understanding fire behavior and quantifying fire risks aboard spacecraft. Continuing these investigations and addressing other knowledge gaps will require a more ambitious experiment in Saffire-IV-VI but, by simulating a more complete fire response scenario and demonstrating post-fire monitoring and cleanup capabilities, these experiments will significantly improve crew safety on all future exploration missions.

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