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LARGE SCALE EXPERIMENTS ON SPACECRAFT FIRE SAFETY

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Full scale fire testing complemented by computer modelling has provided significant knowhow about the risk, prevention and suppression of fire in terrestrial systems (cars, ships, planes, buildings, mines, and tunnels). In comparison, no such testing has been carried out for manned spacecraft due to the complexity, cost and risk associated with operating a long duration fire safety experiment of a relevant size in microgravity. Therefore, there is currently a gap in knowledge of fire behaviour in spacecraft. The entire body of low-gravity fire research has either been conducted in short duration ground-based microgravity facilities or has been limited to very small fuel samples. Still, the work conducted to date has shown that fire behaviour in low-gravity is very different from that in normal-gravity, with differences observed for flammability limits, ignition delay, flame spread behaviour, flame colour and flame structure. As a result, the prediction of the behaviour of fires in reduced gravity is at present not validated. To address this gap in knowledge, a collaborative international project, Spacecraft Fire Safety, has been established with its cornerstone being the development of an experiment (Fire Safety 1) to be conducted on an ISS resupply vehicle, such as the Automated Transfer Vehicle (ATV) or Orbital Cygnus after it leaves the ISS and before it enters the atmosphere. A computer modelling effort will complement the experimental effort. Although the experiment will need to meet rigorous safety requirements to ensure the carrier vehicle does not sustain damage, the absence of a crew removes the need for strict containment of combustion products. This will facilitate the possibility of examining fire behaviour on a scale that is relevant to spacecraft fire safety and will provide unique data for fire model validation. This unprecedented opportunity will expand the understanding of the fundamentals of fire behaviour in spacecraft. The experiment is being developed by an international topical team that is collaboratively defining the experiment requirements and performing supporting analysis, experimentation and technology development. This paper presents the objectives, status and concept of this project.

## INTRODUCTION AND BACKGROUND

Despite decades of research into combustion and fire processes in reduced gravity, there have been very few experiments directly studying spacecraft fire safety under low-gravity conditions. Furthermore, none of these experiments have studied sample and environment sizes typical of those expected in a spacecraft fire. [1] Prior experiments have all been limited to samples no larger than 10 cm in length and width. This stands in stark contrast to all other habitable volumes on earth. In all other cases, (e.g. mines, buildings, airplanes, ships) the standards for fire safety for human occupied structures and vehicles are based upon testing conducted with full-scale fires. The large differences between fire behavior in normal and reduced gravity results in a lack of an experimental data base forces spacecraft designers to base their designs on terrestrial fires and fire standards. While this approach has been successful thus far, there is inherent risk due to the level of uncertainty. Despite their obvious importance, full scale spacecraft fire experiments have not been possible in the past because of the inherent hazards involved in conducting a large fire test in a manned spacecraft. To address this knowledge gap, an experiment was proposed that will be conducted in an expendable spacecraft, enabling the conduct of the experiment without risk to crew or a needed spacecraft.

In October 2011 the NASA Advanced Exploration Systems program funded a project to develop and demonstrate spacecraft fire safety technologies in relevant environments. The keystone of these demonstrations is a large-scale fire safety experiment (demonstration flight) conducted on an International Space Station (ISS) re-supply vehicle after it has undocked from the ISS and before it enters the atmosphere. The AES project team is augmented by an international topical team assembled by the European Space Agency (ESA). This team is comprised by the authors of this article. Each team member brings expertise and funding from their respective space and research agencies. This participation of members from other countries and space agency not only brings additional skills to the science team but also facilitates development of an international approach to spacecraft fire prevention and response. No single experiment can address the range of issues that need to be resolved to fully understand the spacecraft fire risk and to ensure the safety of future flights. The goal of the topical team is to leverage the international capabilities of the team to develop a suite of spacecraft fire safety experiments that will be conducted on appropriate space platforms and to conduct parallel ground-based research [2] to expand the impact of the flight experiments. The current experiment has been designed to address two objectives. The first objective is the development of a flame spread and growth experiment of approximately 1 meter scale. This will be at least an

order of magnitude larger than any prior flame spread experiment and is consistent with the amount of flammable material likely to be in a spacecraft cabin. The second objective is to develop an experiment that will test the flammability limits of materials in low gravity. Supported by the ground-based research by the topical team, the experiment will address both of these objectives and will be discussed in subsequent sections. Development of an experiment of this scale requires a team with a broad range of skills. Not only do the science and technology requirements for the experiment need to be identified, they must be translated into engineering requirements and then expanded to develop engineering drawings and operation concepts for the experiment. In this case, the project team must conduct a trade study to identify vehicles suitable to conduct this experiment.

## SPACECRAFT FIRE SAFETY DEMONSTRATION FLIGHT

### Vehicle Trade Study

The candidate vehicles for this experiment include any of the current or planned ISS resupply vehicles such as the ATV, HTV, or Cygnus<sup>1</sup>. The Spacecraft Fire Safety (SFS) Demonstration project team evaluated various characteristics of these vehicles including:

- Volume of the vehicle
- Weight/Center of Gravity restrictions
- Availability of on-board power
- Availability of communication
- Data downlink options
- Experiment mounting options
- Concept of operations
- Command and control options
- Allowable pressure rise
- Possible experiment configuration
- Availability of ground support
- Launch schedule

The ATV and the Cygnus vehicle were carefully examined for this experiment. Based on schedule and resource availability, the Cygnus vehicle was selected as the most promising option for this experiment.<sup>2</sup> Early in

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<sup>1</sup> The SpaceX Dragon vehicle also will re-supply ISS but it is recovered for re-use. Combustion products from this experiment would enter the vehicle and contaminate the contents thereby complicating the recovery and refurbishment of the vehicle.

<sup>2</sup> In May 2012, funding and schedule concerns eliminated the feasibility of conducting the Spacecraft Fire Safety Demonstration experiment on ATV-5, the last planned ATV mission. One or more experiments similar in concept to that discussed in this paper are being planned for implementation on Orbital Science's Cygnus vehicle.

the development of the project, the European Space Agency (ESA) became interested in this experiment. 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 (BRE Trust/RAEng Chair in Fire Safety Engineering in the School of Engineering at the University of Edinburgh). This team consists of 14 researchers from the European, Japanese, Russian, and U.S. spacecraft fire safety communities and their task is to define research that would be possible from such a low-gravity fire safety experiment. This group has developed the initial science and technology requirements for this experiment. The experiment concept to be discussed in the next section is based on a baseline configuration in the Cygnus vehicle. The SFS Demonstration Project Team has had detailed discussions with personnel from Orbital Sciences to begin the definition of an interface between the experiment and the vehicle. A similar design concept could be implemented in other vehicles.

### Experiment Concept

The concept for this experiment focuses on conducting two types of solid material combustion tests that would be performed on different flights using the same flow duct design. A schematic of the flow duct is shown in Fig. 1 and the flow duct is shown installed in the Cygnus vehicle in Fig. 2. The top and bottom structures on the experiment module are the fan unit on the top and the flow straightener unit on the bottom. The airflow is from the bottom to the top of the experiment module. It is expected that the flow duct will be a rigid structure made with aluminum to enable it to be attached with the standard stowage straps. This duct will ensure a more 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 first test will investigate flame spread and growth in low-gravity to determine if there is a limiting flame size and to quantify the size and growth rate of flames over large surfaces. The flame will propagate over a panel of thin material approximately 0.3 m wide by 1.0 m long, shown in Fig. 1. The ignition method would be a hot wire along the upstream edge. This material will be expected to burn at the anticipated cabin atmosphere. The objective of this test is to quantify the flame development over a large sample in low-gravity. This sample will be more heavily instrumented with multi-view video, thermocouples, and radiometers so that the data can be used to verify numerical simulations of fire spread and development in low-g.

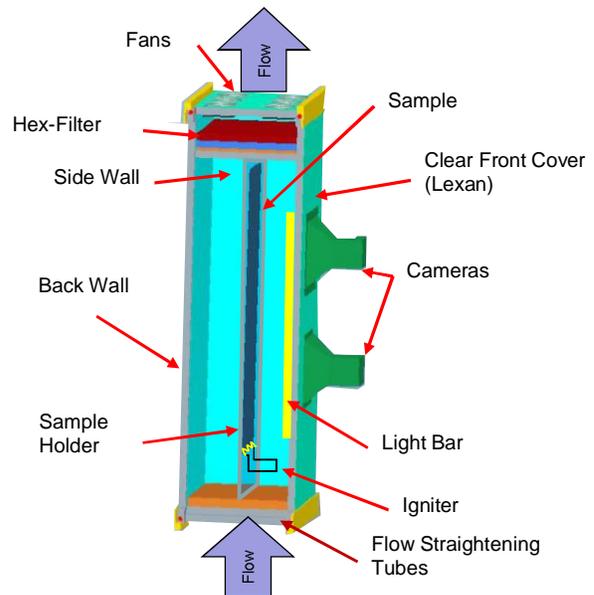


Fig. 1: Schematic of the flow of the Spacecraft Fire Safety Demonstration Experiment. The duct is approximately 50- by 50- by 100-cm.

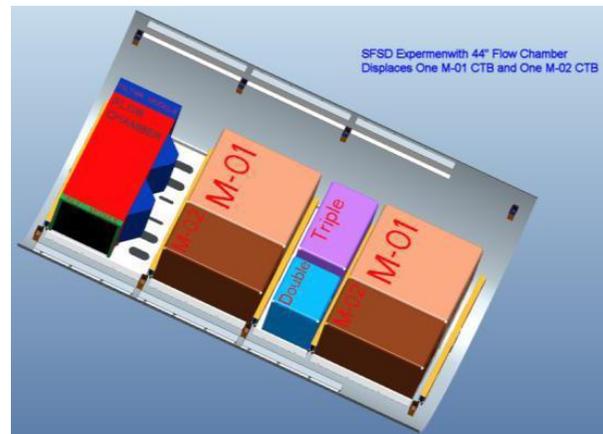


Fig. 2: Experiment Module for the Spacecraft Fire Safety Demonstration shown installed in the Cygnus vehicle. The other objects are standard cargo bags.

Additional diagnostics to be included in the flow straightener and fan units include oxygen sensors, thermocouples, and CO and CO<sub>2</sub> sensors. In addition to filtering particulate, the filter unit could contain the CO sorbent materials developed for post fire cleanup.

The objective of the second set of tests is to investigate the low-gravity Maximum Oxygen Concentration (MOC) flammability limits in long-term low gravity [3]. The configuration for these experiments consists of six to nine samples of varying materials (denoted flammability samples) each having dimensions of approximately 5 cm wide by 30 cm long installed on the same panel in place of the single sample in Fig. 1. These samples emulate the configuration used in NASA-STD-6001

Test 1 [4]. Each sample is ignited at the bottom using a hot wire. The oxygen concentration in the vehicle will be nearly 21% by volume—the same as in the ISS when the hatch was closed. The materials would be selected to be near their normal-gravity or hypothesized low-gravity maximum oxygen concentration in 21% O<sub>2</sub>. This complicates the selection of sample materials because most materials relevant for spacecraft do not have normal-gravity flammability limits near 21% oxygen by volume. [5-7] Camera images would be the primary diagnostics for these tests as the intended result is primarily to determine whether the flame propagates or self-extinguishes.

### Sample Selection

Identifying samples that have flammability limits in the vicinity of 21% oxygen by volume is not trivial. An additional consideration is that re-entry vehicles, in general, are designed to operate within a rather narrow pressure range. Increasing the internal pressure due to the heat release from a combustion event would trigger the opening of a pressure relief valve. Depending on the vehicle design, this may or may not be acceptable as a planned experiment operation. Therefore, this experiment is potentially constrained both by the required flammability limit of the fuel as well as the rate of heat release. Current plans are to constrain the experiment to thin materials that burn in air and will cross over to being non-flammable with limited increase in the sample thickness.

Given the volume of a closed chamber, the heat release created by the combustion of a known mass of fuel is a simple calculation. The complication in determining the pressure rise is that the time history of the pressure rise depends on the balance between the heat release rate of the combustion process and the rate of heat transfer to the cargo and vehicle structure. A transient analysis of this phenomenon can be developed but a detailed verification of this model is required. Experiments have been conducted in a large chamber at NASA GRC in which full-scale samples for the SFS Demonstration experiment can be burned and the rise in gas temperature and pressure rise measured. The chamber Vacuum Faculty (VF)-13 (Fig. 3) has a 149.9 cm inner diameter, and a height of 360 cm, yielding a total volume of 6.35 m<sup>3</sup>. It has a removable steel cap that is 252.1 cm tall. An experimental rack was fabricated to fit into the chamber to support the sample frames (Fig. 4). These sample frames were designed to hold different size samples to facilitate variation of the heat release rate. The frame shown in Fig. 4 could either have the four sample sections ignited simultaneously or sequentially.



Fig. 3: VF 13 test chamber used for pressure rise experiments.

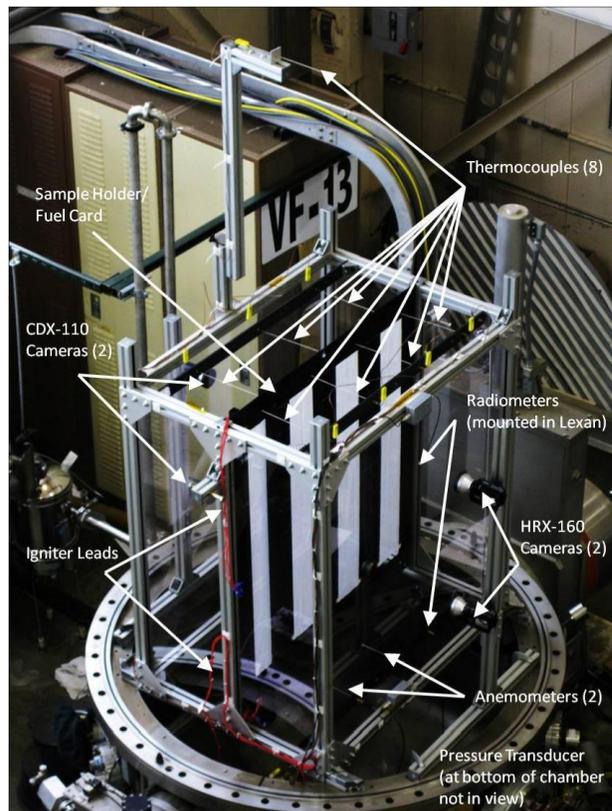


Fig. 4: Experimental Rack in VF13.

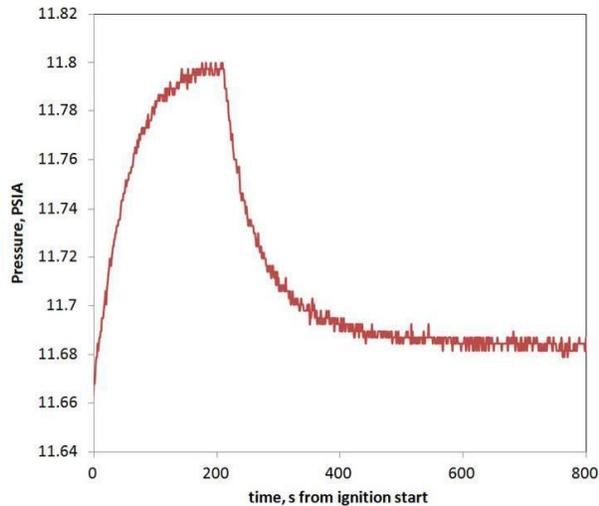


Fig. 5: VF13Experimental pressure curve for a single 12.5- by 100-cm sample ignited at the top. The fuel is 90 grade cotton cheese-cloth with a 4.92 mg/cm<sup>2</sup> density.

Data from these tests are being used to develop and validate models to identify the relevant heat transfer mechanisms and verify code predictions. Fig. 5 contains a typical pressure rise curve. After it is validated against the VF-13 data, the models will then be applied to the experiment in the re-entry vehicle to predict the transient pressure rise and plan the sequence of the experiment. Two models are being developed, a stirred reactor model and a three dimensional numerical model using Fluent<sup>TM</sup>. The stirred reactor model [8] accounts for the energy gain and loss mechanisms that occur during the combustion process. A transient energy balance includes the energy gain due to the burning rate and the associated energy release rate for a typical fuel material to be identified. The energy losses are due to heat transfer by radiation from the flame to the vehicle walls, by convection from the heated gases (which expand as well as are convected) to the vehicle walls, and by conduction from the flame to the fuel-sample holder. The model has successfully predicted results with a smaller sample in a smaller chamber [7] and is being transitioned to reproduce the results in VF-13.

The Fluent model is being developed with the following assumptions: Ke-RNG turbulence model, ideal gas for density calculation, Sutherland model for viscosity, closed volume, constant heat release rate for duration needed to achieve the total heat release, 2.2 million cells. The model has been developed and tested for an adiabatic case (Fig. 6). In the next phases radiative and convective heat losses to the vehicle boundaries will be considered.

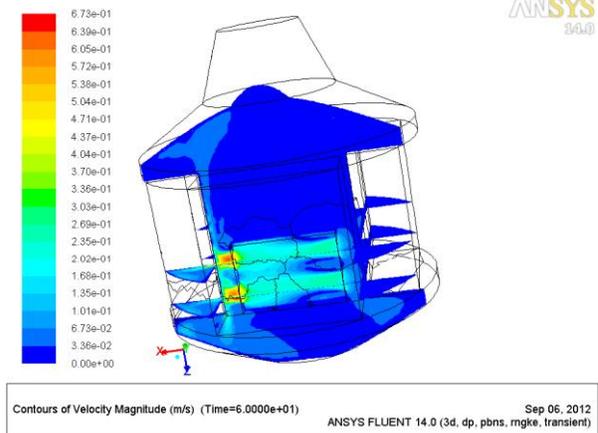


Fig. 6: Fluent model calculation of velocity magnitude in ATV configuration after 1 minute of heat release.

### CONCLUSION

Predicting the end state of an unconstrained fire in a spacecraft and validating NASA's flammability test methods are probably the areas of greatest uncertainty in our effort to ensure the fire safety of future spacecraft. These questions are being address by a material flammability experiment that can be conducted on an ISS resupply vehicle after it has undocked from the ISS and before it reenters the atmosphere. This provides a habitable pressurized environment of considerable size without the hazards associated with a manned vehicle. Exploitation of this opportunity would enable study of practical low-g material flammability phenomena that are important for spacecraft design yet cannot be studied in ISS facilities or other orbital platforms. This experiment has been shown to be feasible on both ESA's ATV and Orbital Science's Cygnus vehicles with the Cygnus as the current base-line carrier. Because of the early interaction with ESA, an international topical team has been formed to develop concepts for that experiment and work towards its implementation. An experimental concept is being developed that will investigate oxygen flammability limits and flame spread over a large fuel sample in a long-term low gravity environment. Additional tasks in the Spacecraft Fire Safety Demonstration Project are being conducted to identify sample materials and verify the predictions of pressure rise in the re-entry vehicle during the experiment. Perhaps the largest challenge is obtaining the proper alignment of resources (both monetary and workforce) and schedule to allow the experiment to be performed within the operating constraints set by the AES Program Office. Nevertheless, this experiment would be a landmark for spacecraft fire safety with the data and subsequent analysis providing much needed verifications of spacecraft fire safety protocol for the crews of future exploration vehicles and habitats.

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