# MICROGRAVITY RESEARCH IN SPACECRAFT FIRE SAFETY

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## ABSTRACT

Fire prevention, detection, and suppression requirements for spacecraft have been developed primarily from established terrestrial and aircraft systems aided by the experience gained from previous space operations. However, the most important factor distinguishing spacecraft fire protection from terrestrial systems is the low-gravity environment that dominates fire and particulate behavior and control in spacecraft. The substantial upward buoyant flow generated by large density gradients in fires at I-g is practically eliminated in spacecraft causing great differences in ignition and combustion processes. At the partial gravity levels that would exist in a lunar or Martian habitat, the effects of buoyancy, convection, and diffusion can combine to produce unique combustion results that are not simple interpolations between 1 g and 0 g results. Thus, practical tire prevention, detection, and suppression practices must be developed for spacecraft and extraterrestrial habitats specifically to respond to the unique aspects of microgravity combustion. Under NASA's Bioastronautics Initiative, there has been a renewed focus on spacecraft fire safety and research projects in material flammability, tire detection and suppression are underway. In this paper, our current understanding of fires in microgravity environments will be reviewed, followed by a discussion of our current research projects in spacecraft fire safety. Trends and issues in fire intervention technology that will guide future research efforts are also presented.

## INTRODUCTION

Current fire safety procedures and policies for manned space flight have resulted primarily by extrapolation from proven terrestrial fire safety research and experience. The stringent material testing requirements, operational guidelines, and experience developed since the early days of the US space program has provided a measure of confidence in the fire safety systems currently on-board inhabited spacecraft. The overall risk of a fire in an inhabited spacecraft is composed both of the probability of occurrence of a fire and the severity of the event if it occurs. As evidenced by incidents that have already occurred in the US space program, the probability of a fire during the lifetime of the International Space Station is significant. Among the scenarios that are by no means rare in a mechanically complex environment are electrical and heating overloads, spills, and resulting aerosols, energetic experiment failures, and ignition of accumulated wastes and trash [1]. Whether such a fire transitions into a serious problem will depend on our collective knowledge of low-gravity fire prevention, detection, and suppression. The potential severity of an even a small fire is increased because a spacecraft cabin is an enclosed volume, which limits the resources for firefighting and the options for crew response and/or escape. Environmental issues, such as the formation and subsequent removal of toxic byprodncts produced by fire suppressants, also add to the severity of a fire by severely taxing an environmental control and life support system even after a fire is extinguished. The combination ofthe probability and severity continues to place on-board fire as one of the greatest risks encountered by astronauts.

A research program aimed at significantly increasing spacecraft fire safety must recognize and address the unique features of fire initiation, detection, and suppression in microgravity environments as well as post-fire cleanup. This paper will first describe some of the spacecraft fire safety research to date that has impacted operations on the US Space Transportation System (STS) Shuttle and International Space Station (ISS) and how these results have led to some of the on-going research. NASA's initiatives and plans for fire safety research at Glenn Research Center will also be discussed.

## PREVIOUS MICROGRAVITY COMBUSTION RESEARCH

The first quantitative experiments on fires under low gravity conditions were first conducted on Skylab in 1974. These tests evaluated the ignitability and flammability of representative spacecraft materials such as mylar, nylon, neoprene-coated nylon, polyurethane foam, and paper in the Skylab atmosphere consisting of 65% $O_2$ in $N_2$ (by volume) at 36-kPa total pressure. In general, these tests showed that microgravity flame-spread rates are consistently less than those in normal gravity by factors on the order of 0.15 to 0.6. Fire suppression was also investigated, and it was learned that extinguishment by water is possible provided sufficient water reaches the burning material. If insufficient water strikes a burning material, it causes a flare-up that can actually scatter burning material and propagate the fire. Fire extinguishment by vacuum was also found to be effective although a significant side effect is that the flame intensifies temporarily because of the induced airflow during the initial moments of venting.

This early work demonstrated that some of the "obvious" terrestrial fire safety solutions may have undesirable consequences in the low gravity environment of space. This prompted experiments to investigate ignition, detection, and suppression of fires in spacecraft more completely. There is now a growing body of information from combustion research conducted in microgravity environments. A summary of space flight projects conducted since 1990 relevant to spacecraft fire safety are listed in Table I [2]. These projects, conducted not only in the payload bay laboratories of the Shuttle but also on Mir, offer observations and measurements of flammability, flame spreads, and smoke characteristics from burning sheet and slab materials in microgravity environments. Of course, these projects have been supported by many ground-based investigations conducted in drop towers and on-board research aircraft.

TABLE 1. EXPERIMENTAL SPACE FLIGHT PROJECTS WITH RESULTS RELEVANT TO SPACECRAFT FIRE SAFETY [2].

| Project | Description | Date |
|---|---|---|
| Solid-Surface Comb. Exper. (SSCE) | Burning of thin-paper and thin-PMMA fuels in quiescent environments to determine effects of oxygen concentration and total pressure on flame spread | 1990 - 1998 |
| Radiative Ign. and Transition to Spread Investigation (RITSI) | Burning of thin paper with central ignition and low-rate forced flow to determine effects of air flow on unconstrained 2- and 3-dimensional flame spread | 1996 |
| Diffusive and Rad. Transport in Fires (DARTFire) | Burning of thin fuels under opposed flow and external heat flux to determine effects of flow and preheat on flame spread | 1996 - 1997 |
| *Mir* Experimental Verification of Material Flammability in Space | Burning of cylindrical plastic fuels under concurrent flow to determine flame characteristics and limiting flows for flame spread | 1998 |
| Forced Flow Flam Spread Test (FFFT) | Burning of flat and cylindrical cellulose and polyethylene fuels under concurrent flow and external heat flux to determine effects on flame length and spread rate | 1996 |
| Microgravity Smoldering Comb. (MSC) | Burning of bulk foamed plastics under flow to determine smolder rate and combustion-product evolution | 1995 - 1996 |
| Forced-Flow Ign. and Flame-Spread Test (FIST) | Evaluation of new method to measure ignition delay and flame spread in microgravity with flow and external heat flux | In prep. |
| Comparative Soot Diagnostics (CSD) | Evaluation of STS and ISS smoke-detector responses to pyrolysis, smoldering, and flaming fires in representative fuel samples | 1996 |

The data obtained from scientific research on microgravity combustion have contributed greatly to the current understanding of the important characteristics of fires in low gravity. Key features of low-gravity fires relevant to fire-safety technology are summarized in Table 2 [2]. Unfortunately, the differences in the key features of fires observed in low gravity from those in I-g indicate that systems deployed for spacecraft fire safety must be significantly different from those used in 1-g environments; e.g., the lack of

TABLE 2. KEY FEATURES OF FIRES IN LOW GRAVITY AND MICROGRAVITY [2].

| Property | Trend | Remarks |
|---|---|---|
| Ignition | Promoted | - Thermally stressed components can overheat rapidly<br>- Particulate spills form flammable aerosols that persist for long times<br>- Burning plastics eject hot material randomly and violently |
| Flame appearance | Altered | - In quiescent environments, flames are often symmetrical in shape and nearly invisible<br>- Under low rates of imposed air flow, flames intensify and become bright and sooty |
| Flammability and flame- spread rate: *Quiescent* **Conditions** | Reduced or extinguished | - Flames propagate slowly or extinguish, due to the accumulation of combustion products |
| Flammability and flame- spread rate: *Low-Flow* **Conditions** | Increased, in some cases to match or exceed normal-gravity levels | - Low rate ventilating flows stimulate low-gravity tires and greatly extend their flammabilityrange and flame-spread rates<br>- Freely propagating flames tend to spread toward the "wind," or into into the oxygen source |
| Detection signatures | | - Flames are often cooler and **less** radiant<br>- Average size and range of soot-particle sizes are greater<br>- Combustion-product nature and auantities are altered |

buoyancy prevents hot gases from being transported away from a thermally stressed component. Without the induced cooling flow, a component can overheat rapidly. Depending on the local velocity and oxygen concentration, the flame may be nearly invisible or bright and sooty [3]. Soot particle sizes are frequently larger than those produced in 1-g because of the longer residence time in the flame zone, which can affect detection techniques and detector design. Furthermore, the quantities and composition of combustion products are altered, which would change sensitivity levels for gaseous tire detectors.

This situation does not improve in the partial gravity environments that would exist in Lunar and Mars habitats. Figure 1 illustrates flame-spread rates over thin paper fuels from airplane and other tests conducted over a range of gravitational accelerations [4, 5]. The Lunar and Martian gravity levels are also indicated. Surprisingly, the flame spread rate actually increases as the gravity level is decreased from I-g conditions with the maximum flammability occurring near the gravity level of the Martian surface.

The minimum atmospheric-oxygen concentration required for downward flame spread on thin paper sheets also varies with gravity level, as shown in Figure 2 [6]. In this figure, the solid symbols are flammable conditions for the stated oxygen concentrations while the open symbols are non-flammable conditions. The minimum oxygen concentration required for flame-spread at Lunar and Martian gravity levels is very near that for microgravity conditions. However, theoretical results (dashed line) indicate a flammability limit that varies greatly with g-level with the minimum occurring near the Martian levels. Although more results are needed to fully understand these data, it is obvious that flame spread and flammability in partial gravity cannot be predicted simply through interpolation between measurements obtained in normal gravity and in microgravity.

Although the preceding discussion presented only a fraction of the research that has been conducted in microgravity, it sufficiently demonstrates the complexities of the problem facing fire safety engineers. The details of the fire ignition, spread, and suppression processes in low and partial gravity levels are very different from those encountered in I-g. When dealing with spacecraft fire safety issues, understanding these differences could be of mission and life-critical importance. This is the focus of our current and planned **fire** safety research and will be discussed in the following section.

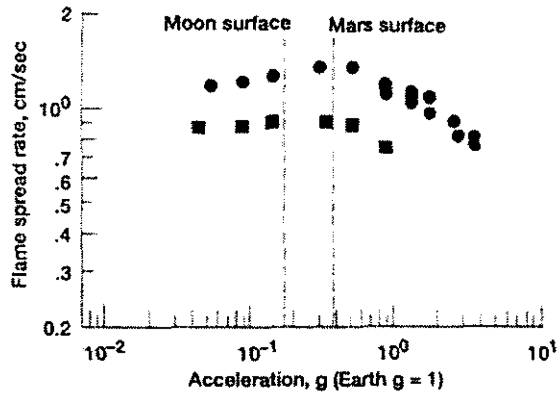

Figure 1. Experimental downward flame-spreadrates for thin paper fuels at 101 kPa total pressure [4].

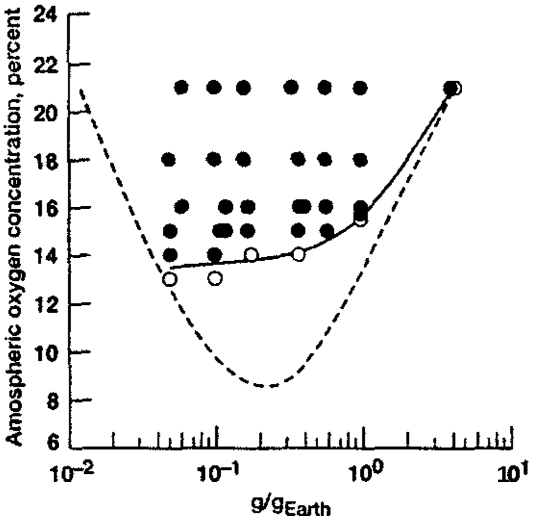

Figure 2. Experimental flammability map for downward burning, thin paper sheets [6]

## NASA'S BIO-ASTRONAUTICS INITIATIVE

Over the past decade, NASA has sponsored a growing amount of microgravity combustion research that has produced considerable insight into the fundamental problems associated with these four areas. Many of the earlier funded projects claimed a strong relevance to fire safety aboard spacecraft but frequently yielded fundamental combustion knowledge rather than results that were directly applicable to spacecraft fire safety issues. A significant increase in our knowledge of fire safety in spacecraft must occur to allow NASA and its international partners to significantly accelerate human endeavors on and beyond earth's orbit. Under NASA's Bioastronautics Initiative, begun to specifically address this need, the combustion science discipline is charged with significantly improving spacecraft fire safety. The performance goal for our discipline is to validate and improve significantly the fire safety principles, policies, and practices used in manned spacecraft on and beyond orbit. The research required to achieve this goal is divided into three major thrust areas (Table 3), which shows a IO-year road map to address fire safety on and beyond orbit: (1) flammability of practical materials in reduced gravity, (2) fire signatures and detection, and (3) fire suppression. Some technical questions relating to these areas are also shown in Table 3. Current research to begin to address these focus areas is discussed in the following sections.

## FLAMMABILITY OF PRACTICAL MATERIALS IN REDUCED GRAVITY

Materials used in habitable volumes of spacecraft are selected from those meeting the prescribed criterion of resistance to flame spread. Currently, all materials to be used in space-vehicles need to meet specific flammability requirements that, in the case of NASA, are provided in the "Flammability, Odor, Offgassing, and Compatibility Requirements and Test Procedures for Materials in Environments that Support Combustion" (NASA-NHB 8060-1). This document specifies two tests that need to be performed before a material is qualified to be used in a space vehicle, the "Upward Flame Propagation Test" (Test 1) and the "Heat and Visible Smoke Release Rates Test" (Test 2). These results of these tests are generally pass/fail with further quantitative evaluation of the results.

The Upward Flame Propagation Test is a normal-gravity test in a configuration where the flame spread is aided by the direction of buoyancy. These tests are conducted in a sealed chamber, shown in Figure 3, filled with air or a representative spacecraft atmosphere [7]. After exposure to a promoted ignition source for 25 s, a material is acceptable if it either fails to propagate a flame away from the igniter or burns for a distance of less than 15 cm. Acceptable materials also cannot scatter hot particles capable of igniting a

TABLE 3. ROADMAP FOR FIRE SAFETY RESEARCH REQUIRED FOR HUMAN EXPLORATION ON AND BEYOND ORBIT.

| TECHNICAL AREA | TIME FRAME<br>2001 - 2004 | <br>2004 - 2007 | <br>2007 - 2010 |
|---|---|---|---|
| Flammability of ***Practical Materials in*** Reduced *Gravity* | - Evaluate potential for deep-sea[illegible] res in non-lg environments<br>- Determine potential for autoigniti[illegible] and explosion of in-situ propellants | | Flammability measurements and correlation from µg to 1g; new validated test methods for material ranking |
| | - Determine flammability and flame spread of plastic and composite materials in partial-g with variations in flow and imposed heat flux<br>- Improved test methods to rank materials | - Determine limiting $O_2$ and flow for flame propagation on the same materials in µg and partial-g<br>-Determine the effects of sub-limit in-situ propellant concentrations in standard and enriched $O_2$ atmospheres on practial material flammability | |
| Fire Signatures and Detection | - **Develop component-level**<br>- Determine method to establish pre-fire and fire signatures of practical materials | - **Develop and demonstrate** integrated sensor **(chemical/smoke)**<br>-Establish pre-fire and fire signatures of practical materials in **low** g | Complete database for fire signatures and demonstration of new detection systems |
| Fire Suppression for Missions On and Beyond Earth Orbit | - Evaluate in-situ [illegible] extinguishants<br>- Develop model of flame growth and stability in practical configurations to extend applicability of database and to guide design of new systems | | Experimentally (µg and partial-g) validated fire suppressant performance, analysis, and models |
| | - [illegible] extinguish[illegible] t st[illegible] t[illegible] y and [illegible] behavior in non-1g environments through [illegible]ys s and modeling<br>- Fundamenta[illegible] and system level trade-off studies of flame-suppression techniques | Analyze and test physical dispersion and techniques for extinguishment<br>- Test and validate flame [illegible] on methods in [illegible] $O_2$ and exotic atmospheres | |

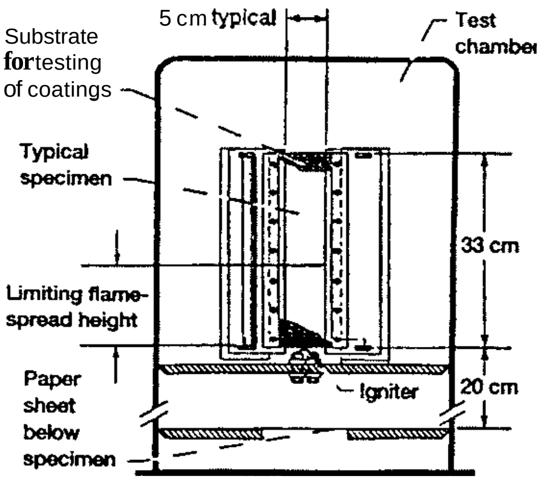

Figure 3. **NASA** Upward Flame Propagation Test (Test 1) apparatus for qualification of spacecraft materials.

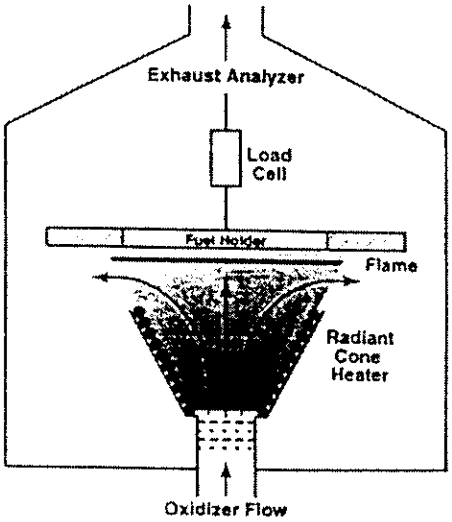

Figure 4. Proposed low flame stretch apparatus for materials flammability testing.

paper sheet mounted below the specimen. The data bank of materials permissible for service on-board spacecraft on the basis of fire resistance is quite extensive and contains pass/fail results for thousands of materials. These normal gravity flammability assessments have been assumed to be conservative with respect to flammability in all environments. **As** previously discussed, materials may be more flammable and have even greater flame-spread rates in microgravity as compared to the normal-gravity reference environment. Hence, the safety factor assumed by relying on this database may be reduced or nonexistent for some material applications. Unfortunately, conducting all material flammability tests in low gravity is not practical because of the time and expense required to conduct such tests.

**A** new materials screening test with a well-understood connection to the real-use extraterrestrial environment is needed, and a new proposed test method developed jointly at **NASA** Glenn Research Center and Johnson Space Center—White Sands, will provide that connection. Microgravity flames in a quiescent or slowly convecting atmosphere are characterized by a low flame stretch rate. The objective of this project entitled "Development of an Earth-Based Apparatus to Assess Material Flammability in Low-Convection Environments for Microgravity and Extraterrestrial Fire-Safety Applications," **(PI:** Olson, **NASA** GRC; Co-I: Beeson and Haas; **NASA** JSC-White Sands), is to develop and test an apparatus that assesses material flammability and flame extinction limit over a range of low-stretch flame environments equivalent to those expected in Earth-orbital and extraterrestrial missions. **A** predictive model to evaluate overall material flammability behavior based on an extension of the data derived from these tests is also to be developed. The apparatus, shown schematically in Figure **4,** uses the unique low stretch geometry in 1 g to simulate the extraterrestrial environment through proper scaling. By using controlled forced-air flow to augment the low stretch obtained by this geometry, stretch levels under Lunar or Martian gravity levels can be simulated. The effect of imposed radiant heat flux on material flammability can be studied with the cone beater.

Even in the simple configuration used in the Upward Flame Spread Test, a considerable amount of combustion physics is occurring. The results of the current tests are generally pass/fail without further quantitative evaluation of the results. The objective of the project, entitled "Material Properties Governing Co-Current Flame Spread in Microgravity" (PI: Torero, University of Maryland), is to analyze the results of these tests to extract several common mass transfer numbers ($B_A$, B„ and B,) used in models of tire growth. The configuration used to model the normal gravity flame-spread tests is shown in Figure 5.

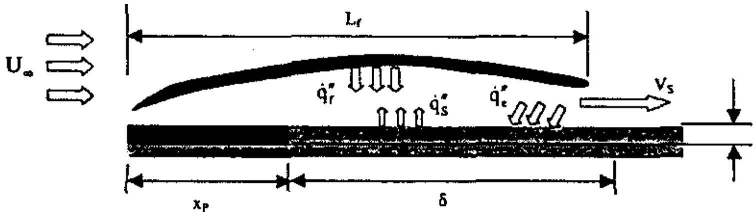

Figure ***5.*** Schematic of co-current flame spread model in **NASA** Upward Flame Propagation Test.

**A** boundary-layer type solution can be obtained for this configuration with the mass transfer numbers incorporated into the boundary conditions to account for mass addition from the surface. $B_A$ and $B_C$ correspond to extreme values, the former being the resulting mass transfer number in the absence of all losses (worst case scenario) and the latter the lowest mass transfer number that can sustain a flame (best case scenario). $B_R$ corresponds to a realistic co-current flame spread scenario that includes heat exchange between the flames and the environment. Determination of these parameters provides the criteria to rank material flammability based on fundamental combustion principles that would be of value for material selection and as criteria for the design of engineering materials. By bounding the fire growth between best and worst case scenarios, a quantitative risk assessment can also be performed.

One of the more probable scenarios for fire initiative on a spacecraft is that it would be a smolder-originated fire resulting from overheated electrical cables, circuit boards, or polymeric material in proximity to these objects. Smoldering combustion is a heterogeneous surface reaction that, while it has a relatively low flame spread and low heat release, can persist for long periods, producing toxic gases and threatening eventual transition to rapid flaming or ignition of adjacent surfaces [8]. Because smoldering is a slow reaction, the longer durations of space flight are required to obtain meaningful data. To expand on the results of a flight experiment conducted in the **STS** Glovebox in 1995-1996, a follow-on project, entitled "Two-Dimensional Smoldering and its Transition to Flaming in Microgravity (PI: Fernandez-Pello, University of California – Berkeley; Co-I: Urban, NASA GRC), will be conducted either on the Shuttle or the ISS. This project will study the two-dimensional forward smolder of polyurethane foam slabs and investigate the effect of the oxidizer flow velocity, oxygen concentration, and external heating on the smolder rate. Conditions under which the smoldering combustion can transition to a flaming fire will also be investigated.

The material certification testing aids fire prevention by minimizing the risk of a small fire becoming a large fire by keeping the rate of flame spread low. Another mechanism for a fire to propagate rapidly would be for a small flaming or smoldering fire to ignite other on-board material. A fourth experiment, entitled "Secondary Fires: Initiation and Extinguishment" (PI: Ross, NASA GRC; Co-I: Urban, NASA GRC and Mell, University of Utah), will determine systematically the conditions that will ignite on-board flammable materials upon passage of an initial premixed gas, firebrand, or aerosol flame. Firebrands are fragments of free-floating burning material that can be rapidly expelled during combustion of effervescing or rapidly vaporizing materials such as plastics, [9], nylon Velcro strips [10], and wire insulation [11]. This experiment will also investigate the conditions at which firebrands can initiate secondary fires on various materials. In these tests, naturally produced firebrands will be simulated using individual or a stream of burning fuel droplets.

## FIRE SIGNATURES AND DETECTION

Spacecraft smoke detectors must detect smoke with a variety of particulate types. Hydrocarbon fuels typically produce soot while overheated plastics produce structures assembled from recondensed polymer fragments [12]. Other materials, such as paper and silicone rubber, produce a smoke that is composed of liquid droplets of recondensed pyrolysis products. The nucleation and growth processes for these different types of smokes are quite varied; consequently, the particulate structure varies with the source. The Comparative Soot Diagnostics (CSD) experiment, which flew in the Glovebox on STS-75, provided the first practically useful data concerning the performance of NASA's smoke detectors and provided particle size information **for** three types of solid smoke particulates. This experiment demonstrated that the microgravity performance **of** the fire detectors could be different from their 1-g performance. This performance difference was attributed to the growth of larger smoke particles in 0-g because of the increased residence time in high smoke concentration regions. The US-built modules of the International Space Station use photoelectric detectors that are most sensitive to the large particles produced from smoldering fires [2]. The Russian-built Service Module also uses photoelectric detectors while the Functional Cargo Block uses ionization detectors. The latter detector is sensitive to small particles produced by flaming fires. In a spacecraft, smoke cannot be transported to a detector by natural convection **so** smoke detectors are aspirated and incorporated in the ventilation system to ensure they "see" the airflow throughout the cabin. However, this also ensures that any particulate in the cabin, such as dust, will be drawn through the detector. False alarms from the photoelectric detectors have been reported during the construction and early habitation of the ISS. To produce smoke detectors that distinguish between dust and smoke, better knowledge of the size distribution and morphology of the particulates is required. Measuring the particulate size distribution of the particulates produced from various fuels is one of the objectives of a project entitled "Characterization of Smoke from Microgravity Fires for Improved Spacecraft Fire Detection" (PI: Urban, NASA GRC; Co-I: Mulholland, Yang, and Cleary, NIST, and Yuan, NCMRfc). This experiment (Figure **6),** is being developed to fly in the Microgravity Science Glovebox (MSG) on the ISS. In

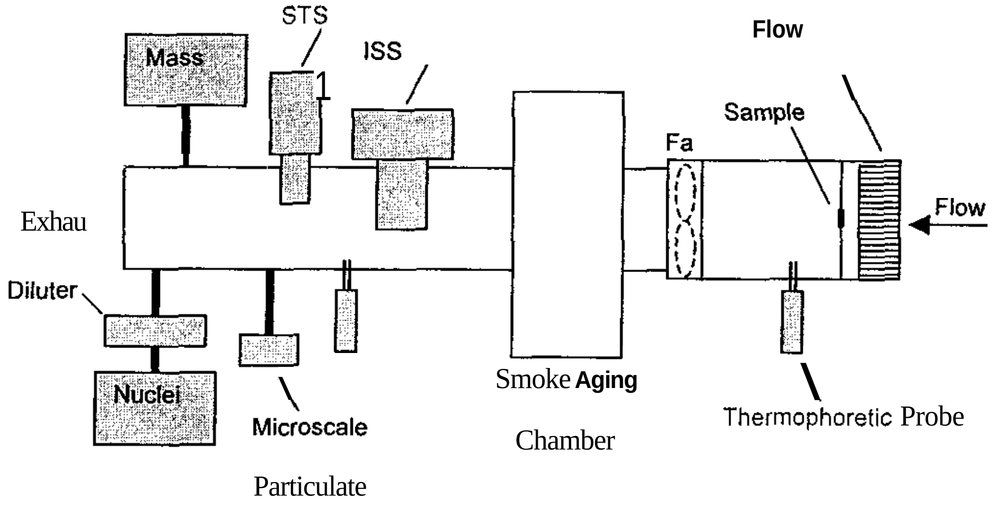

Figure 6. Schematic of the “Smoke” flow tunnel and instrumentation.

addition to the size distributions, it will also evaluate the performance of the STS ionization and ISS photoelectric detectors under a greater range of conditions than in the CSD experiments. As part of this research, a numerical code will be developed to predict the smoke droplet growth as a function of the fuel pyrolysis rate, the thermodynamic properties of the pyrolysis vapor, and the flow environment.

## FIRE SUPPRESSION

The prescribed response to a fire event detected by crew senses or a smoke detector is through the steps of isolation, local power shutoff, and airflow cessation. These actions have been adequate to combat all US fire situations to date. Nevertheless, portable fire extinguishers are present on both the Shuttle and ISS. The portable fire extinguishers on the Shuttle are charged with Halon 1301. The manufacture of this agent is now prohibited by international protocol, but existing suppression systems may be retained. The Shuttle fire extinguishers are supplemented by a fixed, remotely operated, Halon 1301-charged system for use during critical periods, such as re-entry, when the mobility of the crew is limited. The non-Russian modules of the ISS have portable fire extinguishers charged with CO,. There is no centralized, fixed system. The Russian segments of the ISS have water-foam extinguishers similar to those used in other Russian spacecraft.

The ISS extinguishers are sized to release sufficient carbon dioxide to reduce the local ambient oxygen (e.g., in a rack), to half its original concentration within 60 sec [13]. However, in spite of its use, there are many questions about the detailed behavior of CO, as a fire suppressant. For example, because the equipment racks where CO, fire extinguishers are most likely to be used have many internal obstructions, it is unlikely the CO, will have much velocity by the time it reaches the source of the fires. Thus, a slow flow of CO,, rather than a jet flow, may in fact be what is relied upon for extinguishment. Furthermore, once CO, has been dispensed into an inaccessible volume, it will eventually become quiescent. If the fuel source is still hot and issuing flammable vapors while oxygen diffuses back into this region, a smoldering process or fire might reignite. Additional research is required to test the effectiveness of CO, as a fire suppressant at a range of flow speeds and directions.

To begin to answer these questions, a project has begun with the objective of obtaining fundamental knowledge of physical and chemical processes of fire suppression, using gravity and oxygen concentration as added independent variables. This project, entitled “Physical and Chemical Aspects of Fire Suppression in Extraterrestrial Environments (PI: Takahashi, NASA-GRC; Co-I: Linteris, NIST, and Katta, ISS, Inc.), will measure the critical extinction mole fraction for fire suppression agents, such as CO,, $H_2O$ (mist), N„ $CF_3Br$, $CF_3H$, CF„ for selected gaseous, liquid, and solid fuels burning in a cup burner. A unique feature of these tests is that by conducting them on a research aircraft flying proper trajectories, data will be obtained not only at microgravity but also at the partial gravity levels corresponding to those found in Lunar and Martian habitats. In addition to the experimental work, the unsteady fire suppression phenomena will be simulated using a two-dimensional code that includes comprehensive kinetic models for $CH_4$-$O_2$ combustion including diluents and halogenated agent chemistry.

## FUTURE WORK

As discussed in the previous section, research is being conducted in each of the three critical areas relating to spacecraft fire safety. Returning to the roadmap (Table **3),** the current work represents a good first step in the overall NASA plan to significantly improve fire safety principles. However, the following topics require additional attention:

(1) Material Flammability: While several of the on-going projects deal with material flammability issues, evolving and expanding mission objectives require continuous evaluation of new materials. For example, fire initiation and flammability hazards arising from radiation shielding, waste disposal, trash storage, laundry, and household activities must be investigated.

(2) In-Situ Resource Utilization: A Martian habitat will require the in-situ production of propellants, probably methane and oxygen to be produced from on-board stores of hydrogen and water. This processing must be regulated by safety concerns not only for fire but also for high-temperature, high-pressure, and oxygen-handling hazards. In addition, the performance and efficiency of propulsion, fluid, and combustion processes in the partial-gravity and microgravity environments must be determined.

(3) Fire Signatures: Early-warning fire detection can also be achieved by sensing fire signatures or abnormalities that indicate fire or fire precursors. These types of sensors are being developed primarily for detection of fires in aircraft, but they are directly applicable to spacecraft fire detection. The difference is that the fire signature in terms of smoke, gaseous products, heat, radiation, and pressure rise is different in low gravity than at I-g. While these sensors could significantly improve fire detection capabilities, accurate fire signatures for practical material used on spacecraft are required.

**(4)** Post-Fire Cleanup: Even after a fire is extinguished, the immediate well being of the crew and ability to continue the mission may be threatened by structural damage, injury, and atmospheric contamination. Methods to prevent and assess these conditions must be developed and detection and suppression systems developed to prevent their occurrence. Also, subtle, long-term effects of toxic products, hidden damage, and corrosion must be addressed.

## SUMMARY

Fire prevention, detection, and suppression techniques and standards in spacecraft have generally been adapted **from** those of terrestrial and aircraft systems. Although experience in space flight and limited practical fire safety data obtained in reduced gravity have influenced fire safety techniques and procedures, there are still many unknowns concerning how a low gravity environment affects material flammability, flame spread, and combustion products. Microgravity research conducted to date has demonstrated that these differences often produce undesirable consequences fore fire safety. As result, current fire-safety provisions may be, at best, over-designed, and wasteful, or at worst, inadequate for protection in certain fire situations. Microgravity research in the areas of spacecraft fire safety identified in this paper will significantly improve fire safety principles, policies, and practices on existing orbital spacecraft and provide information required for beyond-orbit manned exploration.

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