Fire Accident Testing Evaluation (FATE)

H. D. Ross[1], W. Mell[2], R. Pettegrew[3], M. Hicks[1] and D. Urban[1], [1]NASA Glenn Research Center; MS 500-115, 21000 Brookpark Road, Cleveland, OH 44135; Howard.D.Ross@grc.nasa.gov; [2]University of Utah; 50 South Campus Drive; Salt Lake City, CA 84112 [3]National Center for Microgravity Research; MS 110-3, 21000 Brookpark Road, Cleveland, OH 44135

INTRODUCTION

Over the past decade, NASA has sponsored a growing amount of microgravity combustion research that has afforded considerable insight into a wide variety of fundamental problems. The vast majority of earlier funded projects claimed strong 'relevance' to fire safety aboard spacecraft, but unfortunately the actual connections are often weak (their clear value is in the fundamental knowledge that is gained). In contrast, the experiments we plan are aimed directly at testing, understanding and improving NASA's existing policies and practices toward spacecraft fire safety. In this study, we examine several previously unaddressed issues regarding these fire safety practices and policies. Specifically,

a. NASA Test 1 (an upward flame spread test) is the primary qualification test for materials' use on spacecraft. NASA Test 1, however, does not consider some possible fire sources and some of its assumptions remain unvalidated. These include, among others: a. Premixed fires can occur and heat and ignite solid materials, but these are unconsidered in Test 1; b. Solid materials may be heated well above normal spacecraft air temperatures at the time of an accidental exposure to an ignition source (again unconsidered); c. The effect of firebrands in 1g is assumed to be worst case.
b. Configuration control in microgravity is unvalidated. NASA requires that flammable materials be separated by 5 cm or more, so that fire from one material cannot ignite a neighboring material.
c. There are also concerns with the fire suppression practices and policies. For example, there is uncertainty about the time to extinguish a fire upon termination of ventilation. The application of a jet of suppressant may itself produce firebrands from molten or charring material, and cause an accidental spread of fire. Finally, carbon dioxide, the suppressant of choice for the International Space Station, behaves differently than other diluent, in regard to its impact on the range of oxygen concentrations that will support a flame [1].

The goal of the proposed research is to contribute to improved fire safety practices and policies for spacecraft and Martian habitat through the achievement of the following objectives:

1. Determine systematically the conditions that will ignite onboard flammable materials upon passage of an initial premixed gas, firebrand, or aerosol flame over these materials.
2. Test the effect of firebrands and configuration spacing.
3. Determine the effectiveness of the flow of CO_2 extinguisher or other extinguishing agents.

APPROACH AND PRELIMINARY RESULTS

Objective 3 may be the most important for immediate ISS application, so we are starting with this class of experiments for low-gravity tests. Using a facility that is already built and aircraft-tested (the Spacecraft Fire Safety Facility), we will utilize the configuration of Goldmeer et al[2], i.e. a 2 cm diameter PMMA cylinder over which air flows (stagnation flow geometry). After ignition in 1g and a predetermined time to establish a deeply preheated sample, the gas flow will be switched during an aircraft trajectory from normal air to a preset mixture of extinguishing agent and air (e.g. 20% CO_2, 80% air) and the time for the fire to extinguish will be determined. A variety of gas flow rates, oxygen concentrations, extinguishing agents, sample materials and preheats will be tested. The results will be compared with the depressurization test results of Goldmeer et al.

In support of Objective 1, we will use the same facility with a premixed gas combustion environment, and position secondary materials that are normally found on spacecraft within the environment. Upon ignition of the gas via hot wire, we will determine if a secondary fire occurs. Preliminary feasibility tests were performed in normal gravity. Paper samples were placed in the holder, and the chamber was sealed. After pumping down to vacuum, methanol was introduced into the chamber through a short heated section. The combination of high temperature and vacuum enabled the methanol to fully vaporize. The chamber was then filled to 0.5 atm with a selected gas mixture (the 0.5 atm was used in order to assure chamber safety). The amounts of methanol and air that were introduced were selected so that the mixture was fuel-lean. After several minutes of delay in order to assure that the environment was initially quiescent, a hot wire igniter was energized and ignited the methanol-oxygen-nitrogen mixture at the bottom of the chamber. The subsequent premixed gas flame passed over the paper sample. In a simple test with methanol-air, a double-thick paper sample was charred but did not ignite. This was because of the high speed of the premixed gas flame in 1g, the double-thickness of the paper, and the relatively low oxygen concentration. The test was then repeated with a gas mixture containing 26% oxygen and a single thickness sample. In this case, as shown in **figure 1**, the paper sample rapidly ignited and spread.

In support of Objective 2, we will also perform controlled firebrand experiments, substituting individual or a stream of burning fuel droplets, for the fragments of free-floating burning material that may occur in real spacecraft fires. A droplet generator has already been designed and is in fabrication. A range of configurations will be examined to check the criterion of separation distance required by NASA procedures.

In parallel with the experiments, we are developing a state-of-the-art simulation code for predicting and analyzing the experimental tests. It is recognized that no model presently exists for all of the types of experiments that are described above. Also, the governing equations need to be simplified to simulate the proposed experimental scenarios, not only because it would otherwise be prohibitively expensive to do the computations, but also because the thermo-physical properties are not all known in detail (e.g., thermal degradation of a printed circuit board). The computational efficiency gained by using simple kinetic and radiative transport models will allow the investigators to simulate the effects of obstacles and fuel spacing on the ambient wind and, therefore, transition to flame spread. The effects of obstacles on the delivery of CO_2 suppressant to the flame, in different gravity conditions, can also be investigated.

A simulation code currently under development for use in another NASA project [3] will be modified for use here. This code is the result of combining the numerical approaches of two proven codes developed at NIST: the NIST large eddy simulation fire code and a microgravity flame spread code. The flame spread code has been used to investigate the influence of varying the ambient wind speed (i.e., oxygen supply; [4-6]), the initial flame shape [6], and the width of the cellulosic sample [7]on flame spread, ignition, transition and extinction. Experimental trends have been reproduced and insight into the physics underlying the trends has been obtained. For example, with regard to fire safety, it has been found both experimentally and observed in the simulation results that under certain conditions flames along the open edges of the cellulosic sample spread faster and survive transition more easily than flames which are isolated from the open edges [8]. The simulation results clearly show this to be the result of an increased oxygen supply to the edge flames. Thus, it is expected that, with minor modifications, the simulation code currently under development can be used to obtain qualitative results.

As an illustrative example of how the numerical code will be used to investigate trends, a scenario similar to the aforementioned feasibility experiment was simulated with the two-dimensional version of the flame spread code. The code was used to simulate a fuel-lean gas mixture ignited at one end of the simulation domain and then the subsequent 0g flame traveled over a combustible solid phase fuel. Unlike the 1g feasibility experiments described above, however, the code here is used to examine behavior in zero gravity conditions[1]. The solid-phase and gas-phase kinetic schemes were similar to those used in previous simulations of flame spread over a thermally thin, cellulosic sample. Three conditions were simulated: no ambient wind (**figure 2**); a 2 cm/s ambient wind with the premixed flame spreading in the same direction as the wind; then the premixed flame spreading in the opposite direction of the 2 cm/s wind (**figure 2**). On **figure 2**, color contours of the gas-phase reaction rates are shown for four successive times. The right column of line plots show the mass fraction of the solid phase fuel that is located along $z = 0$ cm. The 0g premixed flame (labeled P on the figure) travels from left to right. Ignition of the fuel gases from pyrolysis of the solid phase occurs at approximately $t = 3.2$ s. The resulting secondary fire (labeled D) spreads in both directions, with its two flame fronts anchored to the solid fuel. When an ambient wind is present, a premixed flame spreading with (against) a wind has less (more) time to heat the solid phase. It may be expected, therefore, that for concurrent winds above a certain speed, no solid-phase ignition will occur. The column on the left side of **figure 3** shows the case of a 2 cm/s wind traveling in the same direction as the 0g premixed flame. The times are the same as in **figure 3**. No ignition of the solid-phase occurred (it did occur when the concurrent wind was 1 cm/s). The column on the right shows the final case in which the premixed flame spreads in the opposite direction of the 2 cm/s ambient wind. In this situation the cellulosic solid ignited even sooner than with no wind (figure 2). Again, the secondary fire (labeled D) spreads, and is anchored to the solid fuel only at its leading edge. These results are meant to illustrate how the model could be used to investigate trends. In order to obtain more quantitative results, modifications to the model are needed – e.g. flame and combustion product radiation, improved kinetics, 3D effects, etc.

[1] The code requires modification before simulations with gravity levels of 1g can be performed.

SUMMARY

By performing parametric experiments both in normal gravity and reduced gravity on the KC-135 aircraft, as well as developing and analyzing related modeling, generality of the interpretation of the experimental findings will be pursued along with direct recommendations for fire safety practices and policies for fire safety on spacecraft and in Martian habitats. This is the principal value of the research.

REFERENCES

1. Honda, L.K. and P.D. Ronney, Combustion Science and Technology, 1998. 133: p. 267-291.
2. Goldmeer, J., Urban, D., and T'ien, J., Fire Safety Journ., 1999. 32: p. 61-88.
3. Mell, W.E., *et al. Simulation of combustion systems with realistic g-jitter.* in *Sixth Microgravity Combustion Workshop.* 2001. Cleveland, OH: NASA CP (this workshop).
4. McGrattan, K.B., *et al.*, Combustion and Flame, 1996. 106: p. 377-391.
5. Kashiwagi, T., *et al. Effects of Slow Wind on Localized Radiative Ignition and Transition to Flame Spread in Microgravity.* in *Proceedings of the Combustion Institute.* 1996, 26.
6. Mell, W.E. and T. Kashiwagi. *Dimensional Effects on Microgravity Flame Transition.* in *Proceedings of the Combustion Institute.* 1998, 27.
7. Mell, W.E. and T. Kashiwagi. *Effects of Finite Sample Width on Transition and Flame Spread in Microgravity.* in *Proceedings of the Combustion Institute.* 2000. Edinburgh, Scotland: The Combustion Institute.
8. Mell, W.E., S.L. Olson, and T. Kashiwagi, *Flame Spread Along Free Edges of Thermally Thin Samples in Microgravity. Proceedings of the Combustion Institute*, 2000. 28.

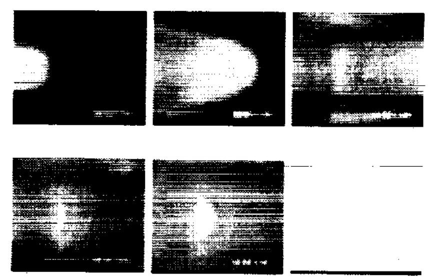

Figure 1: A lean methanol-26% oxygen flame passing over a double-thickness tissue paper. Gravity force is to left of page. A. Ignition by hot wire. B. Methanol flame rising in chamber; C. Methanol flame covers paper and paper ignites at lower edge; D. Flame spread across paper begins; E. Flame spread continues rapidly; F. Paper burns completely. The additional oxygen sustained the paper burning.

Figure 2: Color contours of the gas-phase reaction rate are shown on the left for four separate times, t = 0.1 s, 1.6 s,3.2 s, and 4.7 s. The premixed flame is identified by a P and the diffusion flame, due to the thermal degradation and pyrolysis of the solid phase, is denoted by a D. Conditions are 0g with no ambient wind.

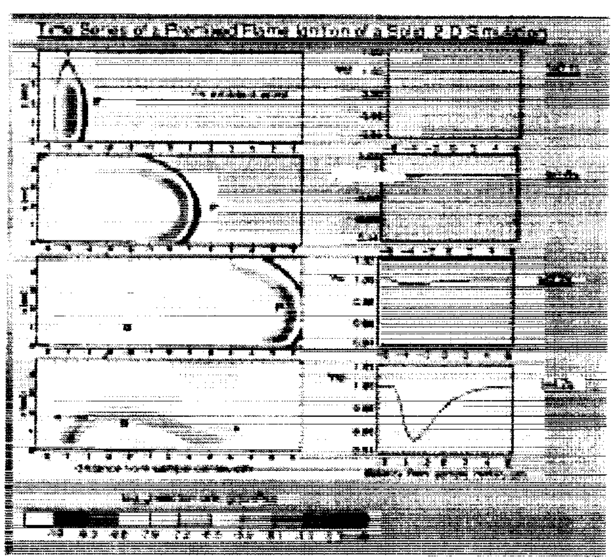

Figure 3: Color contours of the gas-phase reaction rate at four times. As before, the premixed flame is identified by a P and the diffusion flame is denoted by a D. Conditions are 0g with the premixed flame spreading in the same direction as a 2 cm/s ambient wind. Ignition of the solid phase occurs for the premixed flame spreading upwind, since it travels more slowly. Note that ignition occurs earlier for the case of no wind in the previous figure.