OXYGEN CONCENTRATION FLAMMABILITY THRESHOLDS OF SELECTED AEROSPACE MATERIALS CONSIDERED FOR THE CONSTELLATION PROGRAM

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ABSTRACT

Materials selection for spacecraft is based on an upward flammability test conducted in a quiescent environment in the highest expected oxygen concentration environment. The test conditions and its pass/fail test logic do not provide sufficient quantitative materials flammability information for an advanced space exploration program. A modified approach has been suggested – determination of materials self-extinguishment limits. The flammability threshold information will allow NASA to identify materials with increased flammability risk from oxygen concentration and total pressure changes, minimize potential impacts, and allow for development of sound requirements for new spacecraft and extraterrestrial landers and habitats. This paper provides data on oxygen concentration self-extinguishment limits under quiescent conditions for selected materials considered for the Constellation Program.

Keywords: test methods, flammability, aerospace materials, combustion, microgravity

1. INTRODUCTION

Spacecraft fire safety emphasizes fire prevention, which is achieved primarily through the use of fire-resistant materials. NASA STD 6001 Test 1 [1] is the major method used to evaluate flammability of materials intended for use in the habitable environments of U.S. spacecraft. The method is an upward flame propagation test in a quiescent environment using a well-defined igniter flame at the bottom of a vertically mounted sample. A material passes this test if the vertical burn length is less than 15.2 cm and there is no evidence of transfer of burning debris [1]. The upward flammability test is conducted in the most severe flaming combustion environment expected in the spacecraft.

Historically, the Apollo program used an oxygen concentration of 100 % by volume and Skylab used 70 % oxygen. Since then, NASA programs have used much lower oxygen concentrations to reduce the fire risk as much as possible. The Space Shuttle atmosphere is nominally air at ambient pressure, except during prebreathe operations for extravehicular activity (EVA) when it contains 30 % oxygen at 70.1 kPa; the International Space Station (ISS) atmosphere is also nominally air (maximum oxygen concentration 24.1% by volume), except in the airlock, which has the same 30 % oxygen, 70.1 kPa environment as the Shuttle for EVA prebreathe. For the new Constellation program, initial operations to ISS will occur in a nominally air environment. However, for the planned missions to the moon, frequent and extensive lunar EVAs are planned and oxygen concentrations will be somewhat higher to minimize prebreathe times. The current baseline is 30 % oxygen maximum for the Orion Crew Exploration Module and 34 % oxygen maximum for the Lunar Surface Access Module (LSAM); however, these numbers may change.

The existing materials flammability database contains mostly data from Space Shuttle testing in oxygen concentration of 30 % by volume and 70.1 kPa total pressure. Thus, unknown fire risks impede selection for the Constellation Program of environments with higher oxygen content at lower total pressures, which would be more advantageous for important mission operations such as extravehicular activities.

A modified NASA STD Test 1 method has been suggested by NASA Johnson Space Center (JSC) White Sands Test Facility (WSTF) – determination of materials self-extinguishment limits [2]. For the Constellation Program, the flammability threshold information will allow NASA to identify materials with increased flammability risk from oxygen concentration changes, minimize potential impacts, and allow for development of sound requirements for extraterrestrial landers and habitats [3]. This approach will also eliminate the need to retest materials if the baseline maximum oxygen concentration is increased at a later date. This paper provides oxygen concentration flammability threshold information on selected materials intended for the Constellation Program.

2. EXPERIMENTAL

The materials evaluated were selected by NASA JSC Materials and Processes and are described in Tab. 1. The test system consisted of a 1400-L flammability chamber connected to a vacuum pump, with air, oxygen, and nitrogen supplies. Flammability threshold testing in quiescent environments was conducted following NASA STD 6001 Test 1 procedures. The testing was conducted sequentially as recommended by ASTM D 2863 [5], and using a step size of 1 % oxygen by volume. The Upward Limiting Oxygen Indices (ULOIs) were calculated with the "up-and-down method," which has been adopted by both ISO 4589 [4] and ASTM D 2863 for determining the "minimum oxygen concentration required to support combustion of plastics." The ULOI represents the oxygen concentration at which a material passes the NASA STD 6001 Test 1 burn length criteria approximately half the time.

Table 1. Materials Tested

Generic or Trade Name	Chemical Name or Composition	Sample size, mm length x width x thickness
Rigid Plastics		
Lexan® [a] 6006	polycarbonate	152 x 64 x 1.6
Lexan F-6000	flame-retarded polycarbonate	152 x 64 x 3.2
Kydex® [b] 100	polyvinyl chloride/polymethylmetacrylate alloy	152 x 64 x 1.5
Ultem® [a] 1668	polyetherimide	152 x 64 x 2.5
Ultem 2300, 2310, CRS5301	30% glass-filled polyetherimide	152 x 23 x 3.2
SYGEF® [c]	polyvinylidene difluoride	152 x 64 x 1.5
Torlon® [d] 4203	polyamideimide	152 x 25 x 3.2
P1700	polysulfone	152 x 10 x 1.6
Ryton® [e] R-4-06	polyphenylene sulfide	152 x 64 x 1.6
Fabrics		
Nomex® [f] HT90-40 single layer	aromatic polyamide	305 x 64 x 0.3 (See Note 1)
Nomex HT90-40 double layer	aromatic polyamide	305 x 64 x 0.6 (See Note 1)
Armalon TG4060	fluorocarbon/fiberglass	152 x 64 x 0.2
Composites/Laminates		
Fiberite HMF 5-322/54-2A B.G.	graphite/epoxy composite	152 x 50 x 2.1
Bismaleimide/graphite	bismaleimide/graphite composite	152 x 50 x 2.1
Glass-filled PEEK® [g]	25% glass-filled polyetheretherketone	178 x 30 x 3.2
FL 74-24	polyimide/fiberglass laminate	152 x 64 x 2.1
307404	copper clad laminate	152 x 64 x 0.2
CTD-528	graphite/epoxy laminate	152 x 10 x 1.4
CTD-112P	graphite/epoxy laminate	152 x 10 x 1.5
Melamine glass laminate grade G-9-818, Mil-P-15037	amine-formaldehyde glass-filled laminate	152 x 64 x 0.9
Foams		
Zotek® [h] F30	polyvinylidene difluoride	152 x 64 x 26
Solimide® [i] AC-530	polyimide	152 x 64 x 51

[a] Lexan® and Ultem® are registered trademarks of General Electric Company, Pittsfield, Massachusetts.
[b] Kydex® is a registered trademark of Kleerdex Company, Mount Laurel, New Jersey.
[c] SYGEF® is a registered trademark of George Fischer Limited, Schaffhausen Switzerland.
[d] Torlon® is a registered trademark of Amoco Chemicals Corporation, Chicago, Illinois.
[e] Ryton® is a registered trademark of Chevron Phillips Chemical Company, The Woodlands, Texas.
[f] Nomex® is a registered trademark of E. I. du Pont de Nemours and Company, Wilmington, Delaware.
[g] PEEK® is a registered trademark of Whitford Worldwide Company, Wilmington, Delaware.
[h] Zotek® is a registered tradmark of Zotefoams PLC, Surrey, United Kingdom.
[i] Solimide® is a registered trademark of Imi-Tech Corporation, Grove Village, Illinois.

Notes: 1 Nomex was tested in a "J" configuration and at 15 degrees from vertical. The vertical length of the longer leg of "J" configuration was approximately 20 cm. The sample tested at 15 degrees had a length of ~ 30 cm.

For each material, the oxygen concentration was lowered in 1 % steps to determine the maximum oxygen concentration (MOC) that consistently resulted in self-extinguishment. The MOC was the oxygen concentration where at least three samples passed the NASA-STD-6001 burning criteria of less than 15.2 cm burn length; with very few exceptions, the MOC occurred at an oxygen concentration 1 to 3 % below the ULOI. The oxygen concentration flammability thresholds were determined at a fixed total pressure of 70.1 kPa. Most materials were tested in the standard NASA-STD-6001 configuration consisting of vertical samples with the igniter installed approximately 0.6 cm below the leading edge and geometrically centered. Nomex was evaluated in two special configurations. A "J" configuration was used with the igniter placed parallel with the plane of the legs and geometrically centered approximately 0.6 cm below the sample. Samples installed at 15 degrees from vertical were tested with the igniter at approximately 2.5 cm from the lower edge and 0.6 cm underneath the sample. The testing on a material was concluded if at least one sample failed in 30 % oxygen.

3. RESULTS AND DISCUSSION

The experimental test results are summarized in Tab. 2. The materials reported with ULOIs and MOCs less than 30 burned at least 15.2 cm in 30 % oxygen, while the materials reported with ULOIs and MOCs larger than 40 burned less than 15.2 cm in 40 % oxygen.

Among the rigid plastics, polyetherimide, polyamideimide, and polyphenylene sulfide had MOCs larger than 40. Among the fabrics, a fluorocarbon/fiberglass fabric had an MOC larger than 40, while Nomex (an aramid) failed in 30 % oxygen in J-configuration in both single and double layers and at 15 degrees from vertical as a single layer.

The double-layer Nomex installed at 15 degrees from vertical had an MOC of 36. Among the composites, some graphite/epoxies, glass-filled PEEK, polyimide/fiberglass, and copper clad laminate had MOCs larger than 40. Of the two foams tested, a polyvinylidene difluoride (Zotek F30) passed the 15.2 cm burn length criteria in 40 % oxygen. Most rigid plastics melted, transferred burning material, and burned with flame jets; none of the fabrics showed this behavior. None of the composites tested melted or transferred burning material, but most burned with flame jets.

4. CONCLUSIONS AND RECOMMENDATIONS

Many of the materials evaluated passed the 15.2 cm burn criteria in 40 % oxygen at 70.1 kPa. Some of these materials included rigid plastics such as polyetherimide, polyamideimide, and polyphenylene sulfide. A fluorocarbon/fiberglass fabric, a polyvinylidene difluoride foam (Zotek F30) and composites such as glass-filled PEEK, polyimide/fiberglass, copper clad laminate and some graphite/epoxies had also MOCs larger than 40. The results suggest that suitable commercial polymeric materials can be found for most applications in oxygen concentrations above 30 % and that it will be possible to design the Constellation LSAM for internal oxygen concentrations up to the current baseline of 34 % by volume or somewhat higher concentrations if necessary. The specific materials that will be used in LSAM have not yet been selected, so additional testing will certainly be required; but the results are extremely promising.

Additional testing is recommended to determine the oxygen concentration thresholds at higher oxygen concentrations than 40 % by volume, and at different pressures than 70.1 kPa. This approach will allow selection of best materials from the flammability resistance viewpoint. The flammability threshold information will be valuable for new spacecraft and extraterrestrial habitation module designs. In the long term, the data will allow better evaluation of spacecraft fire risks and increased flexibility in selecting spacecraft internal atmospheres, which could lead to increased efficiency of mission operations.

5. REFERENCES

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4. ISO 4589-2. *Plastics – Determination of Burning Behavior by Oxygen Index – Part 2: Ambient-Temperature Test,* International Organization for Standardization, Geneva, Switzerland, 1996.
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Table 2. Upward Limiting Oxygen Indices (ULOI) and Maximum Oxygen Concentrations when Self-Extinguishment Occurs (MOC) for Selected Materials at 70.1 kPa Total Pressures

Generic or trade name	ULOI	MOC	Additional test observations at the MOC (See Note 6)
Rigid plastics			
Lexan® 6006	< 30	< 30	flame jets, melting, burning material falling
Lexan F-6000	41.4	39	flame jets, melting, burning material falling
Kydex® 100	34.4	33	flame jets
Ultem® 1668	42.5	39*	flame jets
Ultem 2300 (See Note 2)	45.2	42	flame jets
Ultem 2310 (See Note 2)	46.4	44	flame jets
Ultem CRS5301 (See Note 2)	45.1	44	flame jets
SYGEF®	37.3	34	flame jets, melting, burning material falling
Torlon® 4203 (See Note 2)	> 40	> 40	none
P1700	31.7	29	flame jets, melting, burning material falling
Ryton® R-4-06	> 40	> 40*	flame jets
Fabrics			
Nomex® HT90-40 single layer (See Notes 3 and 4)	< 30	< 30	none
Nomex HT90-40 single layer (See Note 5)	< 30	< 30	none
Nomex HT90-40 double layer (See Notes 3 and 4)	< 30	< 30	none
Nomex HT90-40 double layer (See Notes 3 and 5)	37.1	36	none
Armalon TG4060	> 40	> 40*	none
Composites/Laminates			
Fiberite HMF 5-322/54-2A B.G.	> 99.5	> 99.5	none
Bismaleimide/graphite	> 99.5	> 99.5	none
Glass-filled PEEK® (See Note 2)	46.8	45	flame jets
FL 74-24	> 99.5	> 99.5	none
307404	> 40	> 40*	flame jets
CTD-528 (See Note 2)	< 30	< 30	flame jets
CTD-112P (See Note 2)	< 30	< 30	flame jets
Melamine glass laminate grade G-9-818	41.6	36.0	flame jets
Foams			
Zotek® F30 (See Note 3)	46.2	45	Melting, burning material falling
Solimide® AC-530 (See Note 3)	35.3	33	None

Notes:
1 Except as noted, all materials were tested in a wing-nut fixture in a standard (vertical) configuration.
2 The samples were held with a single clamp at the top.
3 The samples were tested in a needle rake.
4 The samples were tested in a “J” configuration.
5 The samples were tested at 15 degrees from vertical.
6 Additional test observations for materials with oxygen concentration thresholds > 40 and < 30 were obtained for tests in 40 and 30 % oxygen, respectively.
7 MOCs identified with * passed the NASA STD 6001 burn length criteria on 5 samples.