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Microgravity Effects on Combustion of Polymers

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Contents

Tables

Table | Page

Abstract

NASA Glenn Research Center conducted a cooperative program with the Russian Space Agency Keldysh Research Center, with technical support provided by NASA Johnson Space Center White Sands Test Facility, to investigate polymer combustion in ventilated microgravity in a small combustion tunnel operated on the Orbital Station *Mir*. Reported here are ground test results on flammability characteristics of the test materials for verification of the data and conclusions of the space measurements. It was found that very low forced convective flows can sustain polymer combustion in microgravity. Shutoff of the flow, however, is likely to suppress the combustion, particularly if the fire is in the incipient phase and the oxygen concentration is sufficiently low. Relative flammability rankings obtained in ground tests focusing on standard limiting oxygen index and cone calorimeter heat-release tests would not apply to microgravity environments if the ranking criterion in microgravity is the minimum forced-flow velocity required for sustained combustion. Qualifying ground tests using upward flame propagation appeared to provide conservative results when compared with data obtained in microgravity environments. Convective flows caused by buoyancy in the ground NASA STD 6001 Test 1 far exceeded the minimum forced convective flows required to sustain microgravity combustion. Results indicate that this test provided conservative results for the materials tested in microgravity by sustaining their combustion in less severe oxygen concentration and total pressure conditions than those in which extinguishment occurred in quiescent microgravity environments.

1.0 Introduction

Fire safety in spacecraft emphasizes fire prevention, which is achieved primarily through the use of fire-resistant materials and components. However, the characterization of materials as fire-resistant, as well as the prediction of potential fire paths, requires an understanding of fire initiation and spread in the microgravity (low-gravity) environment of spacecraft. The lack of buoyancy in microgravity reduces both oxygen transport to the flame zone and fuel/oxidant mixing. The lack of natural-convection transport also reduces heat feedback to the thermal-decomposition zone. As a result, flames in quiescent microgravity environments are relatively weak (Friedman 1996). Of necessity, material selection for spacecraft is based on conventional flammability acceptance tests, along with prescribed quantity limitations and configuration control for items that are nonpass or questionable (Friedman 1999). Based on the assumption that the buoyant "normal-gravity" representation is a worst case, these procedures are believed to provide an adequate safety factor when compared to the intended microgravity service.

However, ventilation flows needed in human-crew spacecraft may be sufficient to compensate for the lack of natural convection, possibly causing flammability limits and fire-spread rates to approach or even exceed normal-gravity predictions. Thus, one of the required responses to a recognized fire event in both the Shuttle and International Space Station (ISS) procedures is the shutdown of ventilation flows. If a fire is detected in the Shuttle cabin, the crew will turn off the cabin fan. In an ISS segment, software will shut down ventilation within the affected module. Fire extinguishers are also available in the Shuttle and the ISS if further fire control is necessary.

It is evident that microgravity flammability data can be important supplements to the ground database of acceptable materials. These data help ensure the safe selection of materials and establish sound fire-extinguishment strategies for spacecraft application. To date, the test opportunities to acquire such data have been limited to the very short-time testing in drop towers and research airplanes or to the rare science missions on the Shuttle and *Mir*. For the purpose of practical flammability testing in space, Russian investigators have developed a small combustion tunnel (*Skorost*), capable of studying the flammability performance of solid samples under low concurrent (in the direction of flame spread) air flows (Egorov, et al. 1995). Up to twelve strip or cylinder samples are stored in carousel mounts within the chamber, and individual specimens are chosen for testing by rotation of a mount to place the sample in contact with a centerline igniter. NASA recognized the obvious value of a cooperative project using *Skorost* for long-duration experiments on the Orbital Station *Mir*. The objective of this project is the investigation of the flammability characteristics of practical plastic materials furnished as cylindrical samples. In the project, the Russian Keldysh Research Center provided ground testing, qualification, and data management, with flight support through the Russian Space Center Corporation and additional ground testing and analyses through the All-Russia Scientific Research Institute for Fire Safety of the Russian Ministry for Internal Affairs. (Ivanov, et al. 1999). The U.S. NASA Johnson White Sands Test Facility supplied and characterized the materials and conducted standard and modified flammability testing on the ground. Overall project management was through the NASA Glenn Research Center (formerly Lewis Research Center).

This report describes the results of flammability tests performed in the laboratories of the White Sands Test Facility (WSTF), Las Cruces, New Mexico, on nonmetallic material samples identical to those studied in the U.S./Russian cooperative project. Test results for six reference materials cover those of limiting-oxygen index for flame propagation, average flame-propagation rate, and combustion-product analysis. For the three materials selected for further microgravity testing on *Mir*, test results cover those from the cone calorimeter (peak and average heat release and average mass-loss rate). Adjunct information is found in the appendices. Appendix A lists reference properties of the three materials tested in space. Appendix B summarizes the results of the derivation and calculation of the theoretical limiting flow velocity for flame spread in microgravity for verification of the *Mir* findings. Appendix C presents the test conditions, flame-spread-rate data, and the conclusions of the *Mir* tests taken from the Russian investigation final report, now in preparation as a NASA Contractor Report (Ivanov, Balashov, Andreeva, and Melichov 1999).

2.0 Objectives

The overall program objectives were to investigate gravity effects on polymer combustion and, more specifically, to determine the minimum concurrent air flow to maintain a flame in ventilated microgravity environments. It is assumed that the materials will self extinguish in unheated air atmospheres when the forced-convection flow ceases. The specific objectives of the WSTF technical support were to

- Investigate suitable materials for the study and select three materials to be tested on *Mir*
- Characterize the flammability, heat release, and combustion products of selected materials in ground tests
- Assist GRC on flight test data review and consult with GRC and Keldysh on data interpretation

3.0 Experimental

3.1 Materials

Six materials were investigated for suitability to this study: polymethylmethacrylate (PMMA), high-density polyethylene (HDPE), polyoxymethylene (Delrin®[1]), polyamide (nylon), polyurethane, and epoxy/fiberglass composite. Major criteria for selection included: flammability in the *Mir* environment which consists of an oxygen/nitrogen mixture with uncontrolled oxygen concentration, expected to be between 21 and 25 percent, and approximately 100 kPa total pressure; suitability for Russian ground testing (i.e., minimal heat distortion); and availability of thermal properties data.

3.1.1 Materials for US Ground Testing

Samples of six selected nonmetallic materials were tested for flammability in limiting oxygen-index (LOI) tests, which determine the minimum oxygen concentration to sustain flame propagation, conducted under four variations of propagation direction and atmospheric flow. The strip-sample dimensions are shown in Table 1. For downward flame propagation tests, the polyurethane samples were cut shorter than the rest to prevent their bending during test. For various LOI test sample orientations and flame propagation directions, the sample lengths were different to accommodate equipment restrictions.

The same materials were also tested for upward flame propagation in a fixed, quiescent air atmosphere according to NASA STD-6001, Test 1 (Marshall Space Flight Center 1998). For these tests, the samples were of standard size (30.5 cm long × 6.5 cm wide × supplied thickness – see Table 1 for thickness data). The first three materials in Table 1 (those selected for the *Mir* tests) were also tested for heat release rates and mass loss rates in the cone calorimeter. The cone calorimeter samples were 10 × 10 cm, with thicknesses indicated in Table 1.

[1] Delrin® is a registered trademark of E. I. DuPont de Nemours and Co.

Table 1
Sample Dimensions for Limiting Oxygen Index Tests

Material	4 cm/s Upward Oxygen/Nitrogen Mixture Flow			Quiescent Environment;
	Downward Flame Propagation	Upward Flame Propagation	Lateral Flame Propagation	Upward Flame Propagation
PMMA	150 x 5 x 1.5	100 x 5 x 1.5	60 x 5 x 1.5	150 x 65 x 1.5
HDPE	150 x 5 x 1.6	100 x 5 x 1.6	60 x 5 x 1.6	150 x 65 x 1.6
Delrin	150 x 5 x 1.6	100 x 5 x 1.6	60 x 5 x 1.6	150 x 65 x 1.6
Nylon	150 x 5 x 1.6	100 x 5 x 1.6	60 x 5 x 1.6	150 x 65 x 1.6
Polyurethane	100 x 5 x 1.6	100 x 5 x 1.6	60 x 5 x 1.6	150 x 65 x 1.6
Epoxy/fiberglass	150 x 5 x 1.5	100 x 5 x 1.5	60 x 5 x 1.5	150 x 65 x 1.5

NOTE: Table 1 provides sample length x width x thickness data. All dimensions are in mm.

3.1.2 Materials for *Mir* Testing

Three materials were downselected from this initial group for the *Mir* tests (PMMA, HDPE, and Delrin). The *Mir* samples were in the form of 4.5-mm rods, approximately 6-cm long.

3.2 Test Systems

3.2.1 Flammability Test Systems

The tests in flowing environments were conducted using a Stanton Redcroft Model FTA-1 Oxygen Index apparatus. The test system met the requirements of ASTM G 125 (1997). The apparatus was connected to gaseous nitrogen and oxygen supplies. Before entering the glass column, the test environment was mixed and analyzed for oxygen content with a paramagnetic oxygen analyzer. Tests in quiescent environments were conducted in a 1400-L flammability chamber connected to a vacuum pump, with air, oxygen, and nitrogen supplies. The test system met the NASA STD 6001 Test 1 requirements (Marshall Space Flight Center 1998). Normal speed (30 frames/s) and high-speed (100 frames/s) video recorders were used to evaluate the magnitude of buoyant convective flows.

3.2.2 Heat Release Rate Test System

Heat release rate (HRR) tests were conducted on a controlled-environment cone calorimeter. This apparatus is similar to the cone calorimeter described in ASTM E 1354 (1997), except for modifications that allow testing in controlled oxygen/nitrogen mixtures. The controlled atmosphere cone calorimeter has two unique features not found on the standard unit: the sample combustion chamber is enclosed and is supplied with oxygen/nitrogen mixtures actively analyzed for oxygen concentration; and a remote-operated thermal absorber is used to avoid pretest sample exposure to radiant heating. The apparatus can be used for testing with oxygen/nitrogen mixtures having oxygen concentrations from 15 to 50 volume percent; the instrument can also function as a standard cone calorimeter with ambient air supplied through an opening at the bottom of the combustion chamber.

3.2.3 Combustion Gas Analysis Systems

Carbon monoxide and methane were analyzed by gas chromatograph/flame ionization detector using methanizer to reduce carbon monoxide. The remaining organics were quantified by gas chromatograph/flame ionization detector and identified qualitatively using gas chromatograph/infrared detector/mass spectrometry. Also, the samples were analyzed by ion chromatography for fluoride, chloride, bromide, nitrate, phosphate, and sulfate.

3.3 Test Conditions

3.3.1 Flammability Testing

Limiting oxygen indices were evaluated under the following conditions:

- Downward flame propagation; 4 cm/s upward oxygen/nitrogen mixture flow
- Upward flame propagation; 4 cm/s upward oxygen/nitrogen mixture flow
- Lateral flame propagation; 4 cm/s upward oxygen/nitrogen mixture flow
- Upward flame propagation; quiescent environment

Limited oxygen index tests were conducted at WSTF ambient pressure (85 kPa). A summary of LOI test parameters is presented in Table 2.

NASA STD 6001 Test 1 was conducted in 21 percent oxygen and 79 percent nitrogen at a total pressure of 101.3 kPa.

3.3.2 Heat Release Rate Tests

Cone calorimeter tests were conducted after completion of the *Mir* tests on materials selected for the space tests. Tests were conducted at WSTF ambient pressure (85 kPa) and in oxygen concentrations approximating those in the actual *Mir* tests (22.5, 23.6, and 25.4 percent). The test environment flow rate was approximately 15 g/s, and the samples were exposed to radiant energies of 10, 15, and 20 kW/m^2.

3.4 Procedures

3.4.1 LOI Tests in a Flowing Environment

LOI testing procedures in flowing environments are described in ASTM G 125 (1997). The downward flame propagation tests were standard. Upward flame propagation tests were conducted on vertical samples ignited at the bottom, while lateral flame propagation tests were conducted on horizontal samples ignited at one end. All LOI tests in flowing environments were conducted in 4 cm/s upward flowing oxygen/nitrogen mixtures. For the standard ASTM G 125 procedure, three independent tests were conducted for verification; for the modified procedures, three tests were conducted in environments

Table 2
Test Parameters for Limiting Oxygen Index Tests

Test Parameter	4 cm/s Upward Oxygen/Nitrogen Mixture Flow			Quiescent Environment;
	Downward Flame Propagation	Upward Flame Propagation	Lateral Flame Propagation	Upward Flame Propagation;
Sample orientation	Vertical	Vertical	Horizontal	Vertical
Direction of flame propagation	Downward	Upward	Lateral	Upward
Direction of oxygen/nitrogen flow	Upward	Upward	Upward	NA
Oxygen/nitrogen mixture velocity (forced flow)	4 cm/s	4 cm/s	4 cm/s	NA
Burn criteria	50 mm burn length, or at least 180 s burn time	50 mm burn length, or at least 180 s burn time	50 mm burn length, or at least 180 s burn time	100 mm burn length, or at least 180 s burn time
Method of ignition	Propane flame	Propane flame	Propane flame	Chemical igniter

NOTE: NA means data not applicable.

containing one-percent less oxygen than the environment at which burning criteria had been established, for confirmation of the LOI.

3.4.2 LOI Tests in a Quiescent Environment

LOI testing in quiescent environments was conducted following NASA STD 6001 Test 1 procedures (Marshall Space Flight Center 1998). The tests were initiated at an oxygen concentration estimated to result in sample combustion. If a sample failed the burn criteria, the test continued at a lower oxygen concentration; if the sample passed the burn criteria, the next test was continued at a higher oxygen concentration. This procedure was continued until the minimum oxygen concentration required to fail the burn criteria was achieved. LOI test results in quiescent environments were confirmed by conducting three tests in environments containing 1 percent less oxygen then the environment at which the burn criteria had been met. The burn criteria for these tests were different than those of the tests in flowing environments due to the higher flame height provided by the chemical igniter.

3.4.3 NASA STD 6001 Tests 1 in Air

The NASA STD 6001 Test 1 testing was conducted in air at 101.3 kPa following NASA STD 6001 procedures.

3.4.4 Heat Release Rate Tests

Cone calorimeter test procedures were similar to those described in ASTM E 1354 (1997), with the exception that the test environment supply to the test chamber was controlled.

3.4.5 Combustion Gas Analysis

Polymers were exposed to test environments previously described, ignited with a chemical igniter, and burned. The posttest environment was mixed with circulating fans; a sample was then obtained in a certified-clean stainless steel container, transferred to the appropriate gas analysis system, and analyzed for organic compounds, carbon monoxide, carbon dioxide, and acid gases. The sample transfer was through heated lines to prevent condensations on cold surfaces. The baseline data obtained from burning the igniter were subtracted from the igniter/polymer combustion data.

4.0 Results and Discussion

4.1 Flammability Test Results

The LOI results are summarized in Table 3. During testing, PMMA, HDPE, Delrin, and nylon transferred nonburning, melted material. Some of the melted polyurethane transferred was burning. Epoxy/fiberglass charred. Results from the downward flame propagation tests appeared to be most repeatable. The flame oscillated and became unstable for some materials under upward and lateral flame propagation modes, especially at conditions approaching limiting oxygen values.

Table 3
Limiting Oxygen Indices Under Various Conditions

Material	4 cm/s Upward Oxygen/Nitrogen Mixture Flow			Quiescent Environment;
	Downward Flame Propagation	Upward Flame Propagation	Lateral Flame Propagation	Upward Flame Propagation
PMMA	17.9	17	20	17
HDPE	18.0	18	18	17
Delrin	17.3	12	14	12
Nylon	29.0	22	23	23
Polyurethane	28.0	27	27	27
Epoxy/fiberglass	26.5	17	22	22

The results of NASA STD 6001 Test 1 conducted in air are summarized in Table 4. The NASA STD 6001 Test 1 requirement to support the sample with a spring clamp prevented exposure of side edges; the sample edges were exposed during the LOI tests in flowing environments. This configuration difference between the two tests was the likely contributor, along with the different flow regime, to the difference in results for epoxy/fiberglass. During the upward flame propagation LOI tests on this material, it was observed that the flame advanced primarily along the sample edges where the epoxy resin was leaching out.

Based on flammability test results, PMMA, HDPE, and Delrin were selected for the *Mir* tests. Selected properties of polymers tested in microgravity are included in Appendix A.

Table 4
NASA STD 6001 Test 1 Results in Air

Material	Average Burn Length (cm)	Average Flame Propagation Rate (cm/s)
PMMA	30.5	0.30
HDPE	30.5	0.17
Delrin	30.5	0.27
Nylon	3.2	- [a]
Polyurethane	2.3	- [a]
Epoxy/fiberglass	5.7	- [a]

[a] The propagation rate was not calculated due to the large possible error caused by the short burn lengths.

NASA STD 6001 Test 1on PMMA, HDPE, and Delrin resulted in sustained combustion at lower oxygen concentrations and total pressures than those in which extinguishment occurred in quiescent microgravity environments (Ivanov et al. 1999). Convective flows of approximately 75 to 85 cm/s were observed during ground NASA STD 6001 Test 1 tests conducted on PMMA, HDPE, and Delrin in 21 percent oxygen at a total pressure of 101.3 kPa. Typical human-crew spacecraft are designed to maintain superficial velocities over a range of 6 to 20 cm/s. Larger convective flows encountered in the ground upward flame propagation tests than in a typical ventilated spacecraft indicate that flammability characteristics such as flame spread rates would be less pronounced in the microgravity environment. In an analysis of low-speed concurrent flame spread, it was shown that as the flow velocity was reduced, the flame spread rate, pyrolysis length, and flame length all decreased (Ferkul and T'ien 1994). The reduction of flame spread rate with lowering flow velocities was also confirmed by the *Mir* microgravity experiments. Results indicate that NASA STD 6001 Test 1 provided conservative results for the three materials tested in microgravity by sustaining their combustion in less severe oxygen concentrations and total pressure conditions than those in which extinguishment occurred in quiescent microgravity environments and by producing larger flame-spread rates than would be expected in a typical ventilated spacecraft.

4.2 Heat Release Rate Test Results

The cone calorimeter test results are summarized in Table 5.

The cone calorimeter results indicate that for each material the total heat release was independent of the oxygen-concentration variation from 22.5 to 25.4 percent. The effective heat of combustion for each material was also nearly constant, regardless of the test conditions, in the range of 47 to 50 MJ/kg for HDPE, 25 to 28 MJ/kg for PMMA, and 16 to 17 MJ/kg for Delrin. These data correlate well with published heat of combustion data in oxygen, indicating that the combustion efficiency was very high, and combustion was nearly complete.

The "no ignition" results may have been caused by test method and configuration specificity. The high oxygen/nitrogen mixture flows required by cone calorimeter tests may have prevented achievement of the lower flammability limits at the spark igniter location. When ignition occurred, HDPE, and PMMA had higher peak and average heat release rates than Delrin. Based on HRR data, Delrin may have been the material of choice among the three materials tested. On the other hand, *Mir* results indicate that Delrin sustained combustion at the lowest forced convective flows, meaning from this point of view it is the worst material—as expected from theoretical analysis (Appendix B).

Table 5
Summary of Cone Calorimeter Data

Oxygen (vol %)	Flammability Parameter	Radiant Energy Input: 10 kW/m² HDPE	10 kW/m² PMMA	10 kW/m² Delrin	15 kW/m² HDPE	15 kW/m² PMMA	15 kW/m² Delrin	20 kW/m² HDPE	20 kW/m² PMMA	20 kW/m² Delrin
22.5+/-0.2	Peak HRR (kW/m²)	NI	609	250	848	739	292	1029	669	316
	Average HRR (kW/m²)		432	195	623	520	209	646	497	246
	Total HR (MJ/m²)		48	35	69	50	42	70	51	41
	Average Effective Heat of Combustion (MJ/kg)		25	16	47	26	17	48	27	17
	Average Mass Loss Rate (g/sm²)		16.9	12.3	13.3	19.5	12.3	13	18.6	14.8
23.6+/-0.2	Peak HRR (kW/m²)	NI	NI	210	NT	586	218	1049	662	254
	Average HRR (kW/m²)			161		426	194	649	490	227
	Total HR (MJ/m²)			34		48	35	67	48	36
	Average Effective Heat of Combustion (MJ/kg)			16		27	16	49	26	16
	Average Mass Loss Rate (g/sm²)			10.2		16.1	12.2	13.5	18.6	14.1
25.4+/-0.2	Peak HRR (kW/m²)	NT	NI	242	NI	706	252	1184	783	289
	Average HRR (kW/m²)			187		492	224	734	560	259
	Total HR (MJ/m²)			39		52	40	71	51	40
	Average Effective Heat of Combustion (MJ/kg)			17		28	17	50	27	17
	Average Mass Loss Rate (g/sm²)			11.3		17.7	13.4	14.6	20.5	15.4

NOTES: HRR = heat release rate
HR = heat released
NI = no ignition obtained
NT= no tests conducted

In conclusion, careful cone calorimeter data analysis is needed to avoid misinterpretation for microgravity environment applications. The cone calorimeter test methodology relies on an abundant supply of oxygen, while oxygen availability appears to be controlling in microgravity. Materials with low HRR would need the least amount of oxygen to burn, and consequently, are more likely to support combustion in microgravity.

4.3 Analysis of Combustion Products

The results of combustion products analysis are shown in Table 6.

Table 6
Combustion Products (μg/g of sample)

	PMMA	HDPE	Delrin	Nylon	Poly-urethane	Epoxy/ fiberglass
Formaldehyde	18.4	37.8	2.7	-	-	6.4
Propylene	48.9	79.8	-	9.0	-	16.7
Propyne	31.1	24.5	-	-	-	16.4
Hydrogen cyanide	163.3	129.5	-	939.7	1335.4	-
Acetaldehyde	9.6	43.6	-	14.1	26.7	15.7
Butene	6.8	21.3	-	-	-	-
1,3 Butadiene	12.7	45.2	-	-	-	12.1
C4 Unsaturated aliphatic hydrocarbons	8.7	18.3	-	-	-	25.5
Acrolein	8.6	37.4	-	10.2	10.0	40.5
Acetone	12.7	15.7	-	-	3.3	37.5
C5 Unsaturated aliphatic hydrocarbons	4.3	91.6	-	-	3.2	33.3
2-Methyl propenal	6.2	-	-	-	-	-
Methyl acrylate	96.7	-	-	-	-	-
C7 Saturated aliphatic hydrocarbons	3.4	-	-	-	-	-
Benzene	56.6	127.5	-	5.6	11.7	266.4
Methyl methacrylate	1959.8	-	-	15.5	-	-
Toluene	8.3	16.3	-	-	-	64.8
C9 Saturated aliphatic hydrocarbons	1.5	-	-	-	-	-
Styrene	1.7	8.1	-	-	-	37
Xylenes	-	-	-	-	-	8.5
Phenyl acetylene	-	-	-	-	-	38.2
Benzaldehyde	-	-	-	-	-	0.5
alpha-Methylstyrene	-	-	-	-	-	5.3
Benzofuran	-	-	-	-	-	24.1
C9 Aromatic hydrocarbons	-	-	-	-	-	39.4
Naphthalene	-	-	-	-	-	24.2

Table 6
Combustion Products (μg/g of sample) (concluded)

	PMMA	HDPE	Delrin	Nylon	Poly-urethane	Epoxy/ fiberglass
n-Butane	-	13.2	-	-	-	-
Acetonitrile	-	1.7	3.3	0.8	-	-
Propionaldehyde	-	15.3	-	-	9.5	-
Pentane	-	6.5	-	-	-	-
Pentanal	-	18.1	-	-	-	-
Heptane	-	9.2	-	-	-	-
n-Hexanal	-	8.2	-	-	-	-
C8-11 Saturated and unsaturated aliphatic hydrocarbons	-	56.7	-	-	-	-
Cyclopentanone	-	-	-	34.4	55.7	-
Cyanogen chloride	-	-	-	-	9.7	-
Cyanogen bromide	-	-	-	-	3.3	-
Acrylonitrile	-	-	-	-	12.1	-
Acetic acid	-	-	-	-	13.7	-
Chlorobenzene	-	-	-	-	3.9	-
Benzonitrile	-	-	-	-	13.7	-
Methyl alcohol	-	-	0.8	-	-	-
Methyl formate	-	-	14.7	-	-	-
Ethyl alcohol	-	-	13.4	-	-	-
Dimethoxymethane	-	-	1.0	-	-	-
Carbon monoxide	4112.4	5542.2	3312.6	1436.3	3878.4	6723.1
HF	-	-	-	-	-	-
HCl	-	-	-	-	13	9.8
HBr	-	-	-	-	10	-
HNO_3	24	24	22	250	260	6.5
H_3PO_4	-	-	-	-	-	-
H_2SO_4	5.2	-	-	-	1.9	1.8

NOTE: - means not found as a combustion product.

5.0 Conclusions and Recommendations

The conclusions and recommendations presented here consider the ground test results given in this report, the material properties cited in Appendix A, and the *Mir* microgravity flammability data and conclusions cited in Appendix C.

Very low forced convective flows can sustain polymer combustion in microgravity. Shutoff of forced convective flows in a spacecraft microgravity environment significantly lowers the flame spread rates on thermoplastic polymers and is likely to suppress the fire, if the fire is in its incipient phase and the oxygen concentration is sufficiently low.

In microgravity, oxygen availability has a controlling role in polymer flammability. Among the materials tested, Delrin had the lowest oxygen/fuel mass ratio (1.066) and the highest net heat released per oxygen consumed (14.68 MJ/kg oxygen). Considering its relatively low net heat of combustion (15.7 MJ/kg), it can be concluded that among the polymers tested Delrin requires the least amount of oxygen to burn. As expected, Delrin sustained combustion in microgravity at lower convective flows than other polymers tested.

Increasing oxygen concentration may have a contradictory effect on flammability in microgravity. At increased oxygen concentration, combustion immediately following ignition and molecular diffusion are enhanced; however, the oxygen is consumed more rapidly. In addition, combustion enhancement due to oxygen enrichment could result in higher surface flame propagation, and oxygen replenishment in the combustion zone could occur by propagation in a nonoxygen-depleted zone.

Ranking obtained in ground tests focusing on standard LOI and cone calorimeter heat release rate tests would not hold in microgravity environments, if the ranking criterion in microgravity is the strength of forced convective flows required for sustained combustion. Qualifying ground tests using upward flame propagation appeared to provide conservative results when compared with data obtained in microgravity environments. The convective flows caused by buoyancy in ground NASA STD 6001 Test 1 far exceeded the minimum forced convective flows required to sustain microgravity combustion. The results indicate that NASA STD Test 1 provided conservative results for the three materials tested in microgravity by sustaining their combustion in less severe oxygen concentration and total pressure conditions than those in which extinguishment occurred in quiescent microgravity environments and by producing larger flame-spread rates than would be expected in a typical ventilated spacecraft.

The atmospheric flow in a typical ventilated spacecraft is in the range of superficial velocities from 6 to 20 cm/s. It is desirable to evaluate material flammability in microgravity environments within this forced convective flow range to determine without ambiguity if NASA STD 6001 Test 1 provides conservative pass/fail data under these conditions.

Microgravity testing was limited to materials flammable in air because the flow in the *Skorost* chamber was the *Mir* atmosphere, with its uncontrolled oxygen concentrations varying over the range of at least 21 to 25 percent. The procedure for the *Mir*-based testing required sample ignition and subsequent flame spread in convective flows adequate for these purposes, followed by reduction of convective velocity to determine when quenching occurs. It is desirable to determine how burning materials respond to reduction of forced convective flows in oxygen-enriched environments. This information is of greater importance for materials more commonly used in spacecraft, some of which may not be flammable in air, and specifically for materials with lower heats of combustion which are likely to require less oxygen during combustion.

The data obtained on *Mir* has a great value for spacecraft safety. However, the measurements were limited to flow, oxygen concentrations, and visual diagnostics. Additional diagnostics are desirable for a more complete characterization of burning behavior such as thermal imaging, interferometry, and combustion product species in flames. This information would also be valuable for modeling.

Finally, investigation of smoldering combustion in microgravity should be conducted, because smoldering is less likely to be controlled by oxygen availability.

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Appendix A

Selected Properties of Polymers Tested in Microgravity

Table A-1

Selected Properties of Polymers Tested in Microgravity

	HDPE	PMMA	Delrin	Reference
Molecular weight (monomer)	28.03	100.06	30.01	a
Gross heat of combustion (MJ/kg)	46.2 to 46.5	26.64	16.93	a
Net heat of combustion (MJ/kg)	43.1 to 43.4	24.88	15.65	a
Net heat released/oxygen consumed (MJ/kg O_2)	12.63	12.97	14.68	a
Oxygen-fuel mass ratio	3.425	1.919	1.066	a
Heat capacity (solid) (kJ/kg ºC)	1.83 to 2.30	1.44	1.46	a, b
Composition (wt%)				
C	85.63	59.99	40	
H	14.37	8.05	6.71	
O	0	31.96	53.28	
Adiabatic flame temperature (ºC)	1695 to 1855	1610 to 1815	1520 to 1720	c
Density (kg/m^3)	950	1170	1400	a, b
Minimum radiant flux for ignition (kW/m^2)	19	18	17	a
Energy required for ignition (kJ/m^2)	1500 to 5100	1300 to 4200	2100 to 6000	a
Autoignition temperature (K)	--	454	469	f
Effective heat of gasification (MJ/kg)	1.5 to 2.7	1.6	2.4	a
Thermal conductivity (cal/[s K cm] x 10^4)	11 to 12.4	6.4	5.5	b, d
Pre-exponential factor (g/cm^2 s atm^n)		1.36 x 10^5		d
Activation energy (cal/mole)		36 x 10^3		d
Decomposition temperature (ºC)	335 to 450	170 to 300		e

[a] *Fire Protection Handbook.* National Fire Protection Association, Quincy, MA, 1991.

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Appendix B

Theoretical Estimation of Limiting Flows for Sustained Combustion Under Controlling Oxygen Transport Conditions

Assumptions

- Initial conditions sufficiently severe to allow flammability
- After ignition, decreasing oxygen supply in time to the combustion zone induces an unsteady state until near extinction, when oxygen mass transport to the combustion zone becomes controlling
- Molecular diffusion of oxygen and laminar flow of space cabin environment supply in the test chamber
- Diffusion coefficient a weak function of composition
- Flame propagation sufficiently slow to prevent significant oxygen replenishment in the combustion zone by propagation in a nonoxygen-depleted zone
- Gas-phase combustion

Estimation of Limiting Flows for Sustained Combustion under Controlling Oxygen Transport Conditions

1. Estimate oxygen supply to the combustion zone by molecular diffusion.

The net rate of oxygen diffusion in a stationary fluid is given by

$$N_o = -D_v \frac{\partial c}{\partial s} \qquad \textbf{(B-1)}$$

where:

N_o = rate of oxygen diffusion, g-moles/(s cm^2)
c = concentration, g-moles/cm^3
s = distance, cm
D_v = diffusivity, cm^2/s

Assuming a constant diffusivity, equation (B-1) integrates to

$$N_o = \frac{D_v \mathrm{P}}{\mathrm{RTB_F}}\left(y - y_i\right) \qquad \textbf{(B-2)}$$

where:

P = absolute pressure, atm
R = universal gas constant, (cm^3 atm)/(g-mole K)
T = temperature, K
B_F = layer thickness, cm
y = oxygen mole fraction
y_i = oxygen mole fraction at the interface

$$D_v = \frac{BT^{\frac{3}{2}}\sqrt{\left(\left(\frac{1}{M_1}\right)+\left(\frac{1}{M_2}\right)\right)}}{\Pr_{12}^2 I_D} \qquad \textbf{(B-3)}$$

where:

B	=	$\left(10.85 - 2.50\sqrt{\frac{1}{M_1}+\frac{1}{M_2}}\right)10^{-4}$
M_1, M_2	=	molecular weights of components 1 and 2
r_{12}	=	collision diameter, angstroms = $[(r_o)_1+(r_o)_2]/2$
r_o	=	$1.18\ V_b^{1/3}$
V_b	=	molecular volume of gases , cm^3/g-mole
I_D	=	collision integral of diffusion, function of kT/ε_{12} (Hirschfelder et al. 1949[1] and Wilke and Lee 1955[2])

$$\frac{\varepsilon_{12}}{k} = \sqrt{\left(\frac{\varepsilon_1}{k}\right)\left(\frac{\varepsilon_2}{k}\right)}$$

k	=	Boltzman constant = 1.38×10^{-6} ergs/K
ε_{12}	=	energy of molecular interaction, ergs

For an estimated diffusion transfer area of 3.5 cm^2, the oxygen supply to the combustion zone by molecular diffusion was estimated at:

For HDPE: 0.1575×10^{-3} g-moles/s
PMMA: 0.1554×10^{-3} g-moles/s
Delrin: 0.1519×10^{-3} g-moles/s

2. Estimate limiting flows for sustained stable combustion under controlling oxygen transport conditions.

For 4.5 mm diameter polymer rods with oxygen-fuel mass ratios of 3.425, 1.919, and 1.066 for polyethylene, PMMA, and Delrin, respectively (see Appendix A), and for a regression rate of 0.25 mm/s, the theoretical amount of oxygen needed in addition to the oxygen supplied by molecular diffusion for sustained stable combustion was evaluated at:

For HDPE: 0.2325×10^{-3} g-moles/s
PMMA: 0.1321×10^{-3} g-moles/s
Delrin: 0.0381×10^{-3} g-moles/s

For a controlled surface area of 25 cm^2, the resultant limiting forced convective flows for sustained stable combustion are shown as a function of the convective flow stream oxygen concentrations in Figure B-1.

---

1 Hirschfelder, J. O., Bird, R. B., and Spotz, E. L. "Viscosity and Other Physical Properties of Gases and Gas Mixtures." *Transactions of the ASME*, 71 (1949): p. 921-937.

2 Wilke, C. R. and C. Y. Lee. "Estimation of Diffusion Coefficients for Gases and Vapors." *Ind. Eng. Chem.*, 47 (1955): p. 1253.

3. Comparison of Estimated Limiting Flows with *Mir* Data

Estimates of limiting flows for sustained combustion may be compared with the experimental values of limiting flows obtained in the *Mir* tests (Ivanov, Balashov, Andreeva, and Melikhov 1999). These data are presented in Table B-1. The experimental values are for four tests with each of the three materials, conducted on three days with measured oxygen concentrations of 22.5 and 23.6 (one test on each day) and 25.4 percent (two tests on that day). The *Mir* data show the lowest concurrent atmospheric velocity for sustained combustion and the highest velocity for extinguishment. These velocities more or less bracket a defined limiting flow. The theoretical values for comparison are interpolated at the appropriate oxygen concentration from Figure B-1. Brief comments on the comparative results follow.

Table B-1
Limiting Concurrent Atmospheric Velocities for Sustained Combustion

Material	Atmospheric Oxygen Concentration, %	Experimental Velocity, cm/s		Theoretical Limiting Velocity, cm/s
		Minimum for Sustained Combustion	Maximum for Extinguishment	
Delrin	22.5	1.0	a	0.16
	23.6	0.5	0	0.15
	25.4	0.3/0.3	0/0	0.14
PMMA	22.5	2.0	0	0.53
	23.6	1.0	0.5	0.51
	25.4	0.75/0.5	0.5/0	0.47
HDPE	22.5	8.5	0	0.94
	23.6	1.0	0	0.90
	25.4	1.0/0.5	0.5/0.3	0.83

[a] Sample continued to burn under quiescent conditions

Delrin

- The theoretical values of limiting flow velocity for sustained combustion are low, and they vary little for the range of *Mir* oxygen concentrations (22.5 to 25.4 percent).
- The theoretical values of limiting flow velocity are within the experimental range of flammable/nonflammable values, confirming the *Mir* results.
- With one exception, a no-flow condition (zero velocity) causes extinguishment (*i.e.*, it is below the limiting velocity) in theory and in experiment.

- The exception was the Delrin experiment at 22.5% oxygen, where the sample continued to burn at zero velocity and had to be quenched eventually by purging. The investigators considered this an anomalous behavior, perhaps induced by sample preheating through multiple ignition attempts.

PMMA

- The theoretical values of limiting flow velocity are somewhat dependent on oxygen concentration, and they range around 0.5 cm/s for the *Mir* environments.

- The theoretical values of limiting flow velocity are either within the experimental range of flammable/nonflammable values, or agree with the extinguishment data (at 23.6 % oxygen), confirming the *Mir* results.

- No flow causes extinguishment in theory and in experiment.

HDPE

- The theoretical values of limiting flow velocity are more dependent on oxygen concentration than PMMA, and they range around 0.9 cm/s for the *Mir* environments.

- The theoretical values of limiting flow velocity are within the experimental range of flammable/nonflammable values for the data at 22.5 and 23.6% oxygen and for one test at 25.4% oxygen, confirming the *Mir* results.

- The exceptional case at 25.4% oxygen was Sample 12, which was distorted by exposure to flame to adjacent samples, which possibly induced self-heating to sustain combustion at lower velocities.

- No flow causes extinguishment in theory and in experiment.

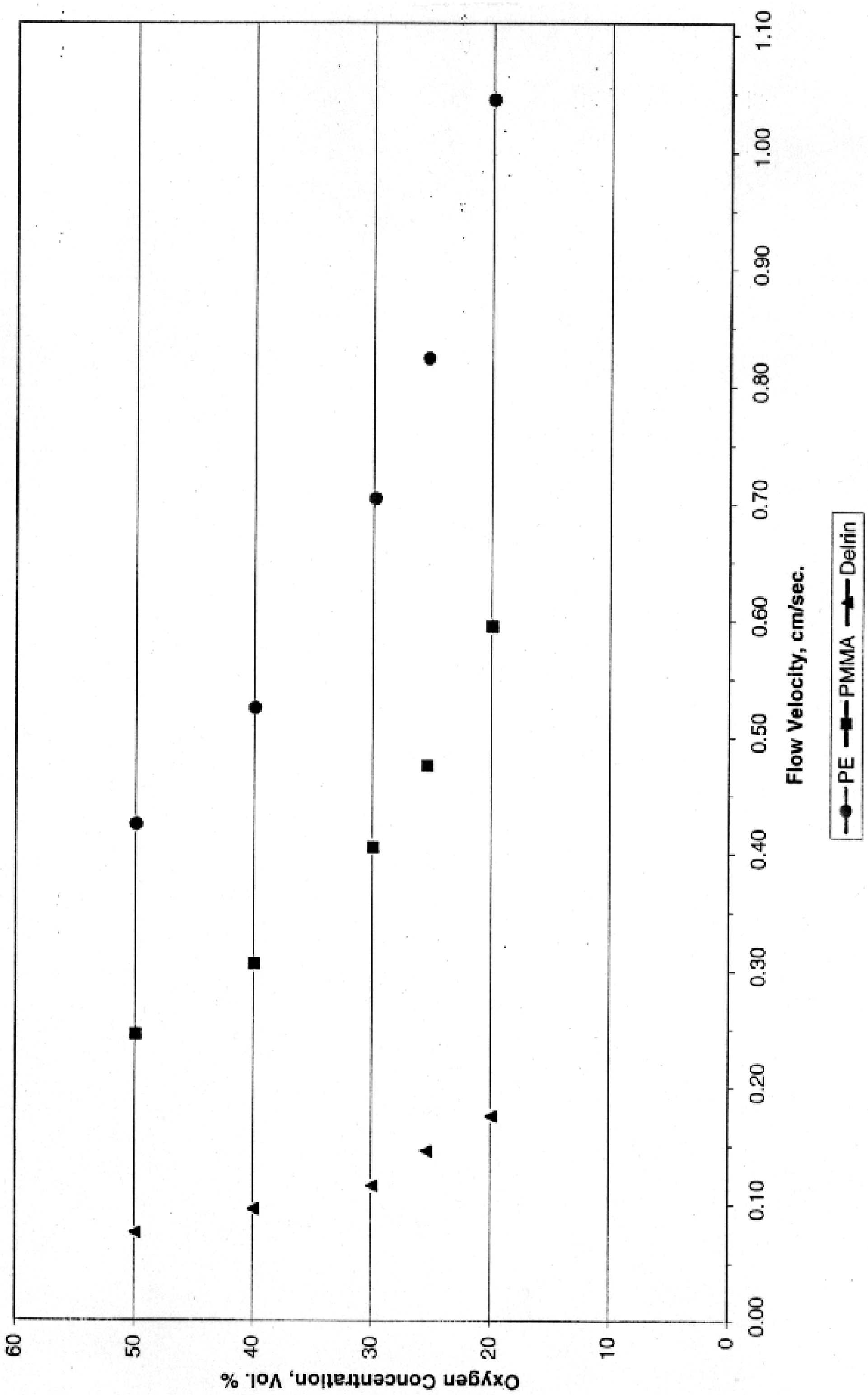

Figure B-1
Theoretical Estimates of Limiting Flows for Sustained Combustion

Appendix C

Experimental Verification of Material Flammability in Space (Excerpt)

NASA CR 1999-209405

EXPERIMENTAL VERIFICATION OF MATERIAL FLAMMABILITY IN SPACE

Final Report

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Table C-1
Actual Schedule for Material-Flammability Evaluation in Skorost on *Mir*
(Forced flow test conditions in microgravity and results which indicate flow conditions that did not support flammability)

Material	Sample #	Flow Velocity (cm/s) Ignition	First Quarter Length of Sample	Second Quarter Length of Sample	Third Quarter Length of Sample	Balance of Sample
Delrin	1	2.0	1.0	0.0[a]	--	--
	2	4.0	1.0	0.5	0.0[a]	--
	3	4.0	2.0	0.3	0.0[a]	--
	4	4.0	7.0	0.3	0.0[a]	--
PMMA	5	2.0	2.0	0.0[a]	--	--
	6	2.0	1.0	0.5[a]	--	--
	7	2.0	8.5	0.5	0.0[a]	--
	8	2.0	4.0	0.75	0.5[a]	--
High-Density Polyethylene	9	8.5	8.5	0.0[a]	--	--
	10	8.5	4.0	2.0	1.0	0.0[a]
	11	8.5	2.0	1.0	0.5[a]	--
	12[d]	8.5	1.0	0.5	0.3[a]	--

[a] Flow velocity where the flame extinguished eventually.

Authors' note: The following information is supplemental to Table C-1 and was determined during a meeting at the NASA White Sands Test Facility in January 1999.

The *Mir* environmental conditions during microgravity flammability testing were as follows:

- All testing was performed at an ambient temperature of 20 ºC;
- Samples 1, 5, and 9 were tested at 22.5% oxygen concentration, 709 mmHg total pressure, and 5.2 mmHg carbon dioxide partial pressure;
- Samples 2, 6, and 10 were tested at 23.6% oxygen concentration, 722 mmHg total pressure, and 5.8 mmHg carbon dioxide partial pressure; and
- Samples 3, 4, 7, 8, 11, and 12 were tested at 25.4% oxygen concentration, 715.5 mmHg total pressure, and 6.3 mmHg carbon dioxide partial pressure.

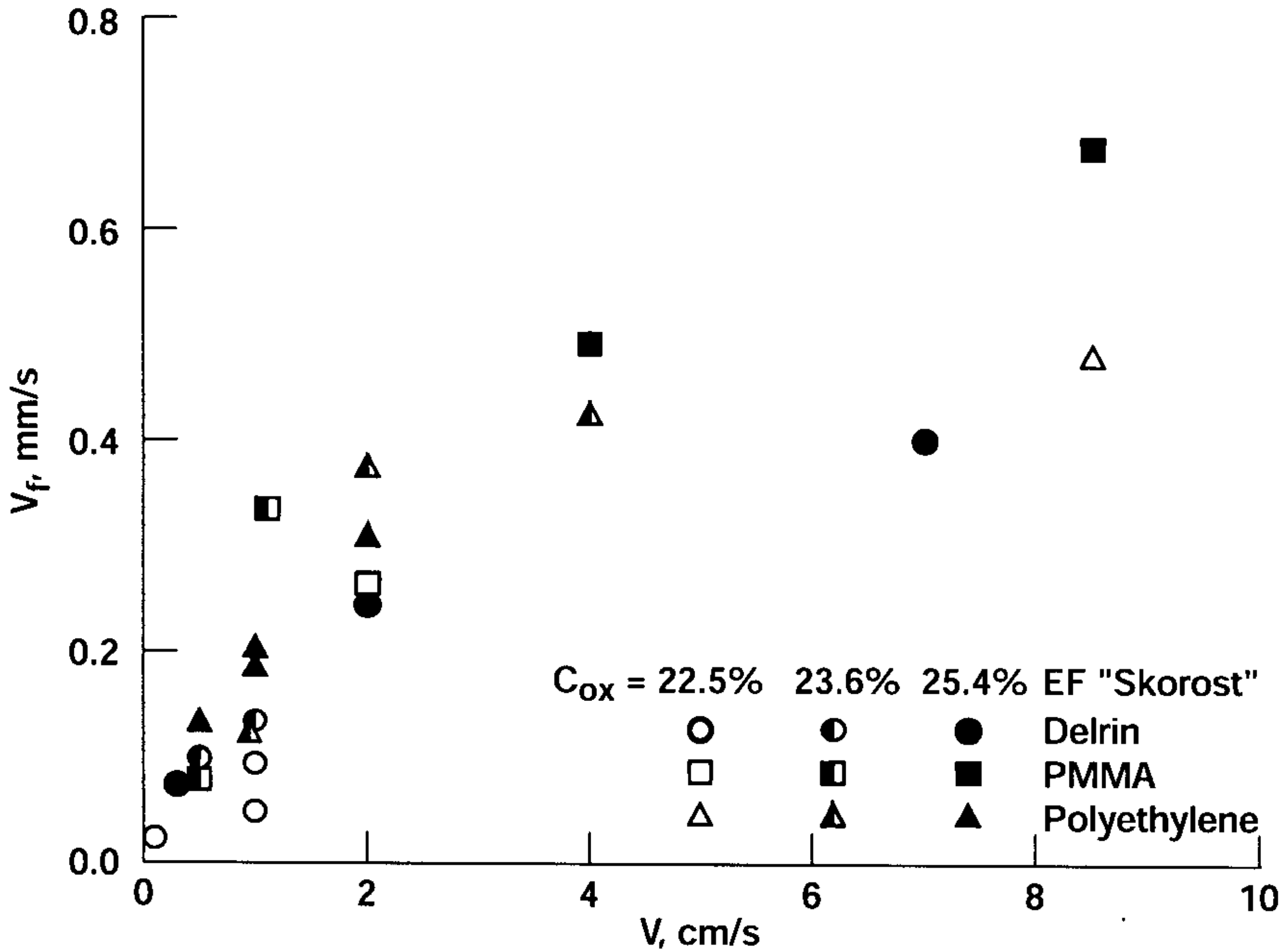

Figure C-1
Flame-Spread Rate (V_f) for Test Samples as Function of Concurrent Flow Velocity (V),
Measured in Space on the Skorost Apparatus

Conclusion

The third series of space experiment in the *Skorost* apparatus was conducted and videotaped in October of 1998 on the Orbital Station *Mir*. The combustion of twelve selected cylindrical samples of three plastic materials, Delrin, PMMA, and high-density polyethylene, was observed in microgravity. The diameter of each sample was 4.5 mm, the flow velocity was from 0.3 to 8.5 cm/s, and oxygen concentration was elevated (ranging from 22.5 to 25.4 percent).

The characteristics of melting material combustion were identified in microgravity for the modes close to limiting. The limiting flow velocities were obtained for tested materials:

- for PMMA, V_{lim} = 0.5 cm/s at C_{ox}, = 23.6 percent
- for polyethylene, V_{lim} = 0.3 to 0.5 cm/s at C_{ox} = 25.4 percent
- for Delrin, V_{lim} < 0.3 cm/s at C_{ox} = 25.4 percent

The values for a limiting flow velocity obtained in the space experiment appear to be lower than the values obtained in the ground testing with apparatus with suppressed convection (horizontal Narrow Channel).

It has been demonstrated that at flow shutoff the extinction in microgravity occurs in 5 to 20 s, which is significantly lower than the extinction time obtained during the ground testing. The shorter extinction time is favorable for fire-safety system operation in space compartments, where the fire-system response is based on vent-flow shutoff.

It has been shown that, if the concurrent flow velocity V decreases, the flame-spread rate V_f will decrease, from V_f = 0.5 to 0.75 mm/s at V = 8.5 cm/s to V_f = 0.05 to 0.01 mm/s at V = 0.3 to 0.5 cm/s.

Based on the analysis of data obtained on nonmetallic material flammability in space, it is proposed to continue the space-experiment program in *Skorost* and *Skorost*-M.

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NASA Glenn Research Center conducted a cooperative program with the Russian Space Agency Keldysh Research Center, with technical support provided by NASA Johnson Space Center White Sands Test Facility, to investigate polymer combustion in ventilated microgravity in a small combustion tunnel operated on the orbital station *Mir*. Reported here are ground test results on flammability characteristics of the test materials for verification of the data and conclusions of the space measurements. It was found that very low forced convective flows can sustain polymer combustion in microgravity. Shutoff of the flow, however, is likely to suppress the combustion, particularly if the fire is in the incipient phase and the oxygen concentration is sufficiently low. Relative flammability rankings obtained in ground tests focusing on limiting oxygen index and cone calorimeter heat-release tests would not apply to microgravity environments if the ranking criterion is the minimum forced-flow velocity required for sustained combustion. Convective flows caused by buoyancy in the ground NASA STD 6001 Test 1 far exceeded the minimum forced convective flows required to sustain microgravity combustion. Results indicate that this test provided conservative results for the materials tested in microgravity by sustaining their combustion in less severe oxygen concentration and total pressure conditions than those in which extinguishment occurred in quiescent microgravity environments.

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