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COMPARISON OF FLAME SPREADING OVER THIN FLAT SURFACES IN NORMAL GRAVITY AND WEIGHTLESSNESS IN AN OXYGEN ENVIRONMENT

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16. Abstract

A test program was conducted to observe burning characteristics of solids during weightlessness in a 3.45-N/cm^2 abs (5-psia) oxygen atmosphere. Results obtained from tests conducted in both 1- and 0-g environments were compared. Flame profile and spread pattern were photographed, and flame spread rate was measured over thin, square-shaped, paper and plastic specimens; the specimens were oriented vertically and horizontally in a sealed combustion chamber. During weightlessness the profile of the flame was found to be rounded or dome-shaped for either orientation while the flame spread in a uniform circular pattern over the specimen surface. Flame spread rates were lower in 0- than in 1-g.

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SUMMARY

A test program was conducted to observe burning characteristics of solids during weightlessness in a 3.45-N/cm^2 abs (5-psia) oxygen atmosphere. Results obtained from tests conducted in both normal-gravity and zero-gravity environments were compared. Flame profile and spread pattern were photographed, and flame spread rate was measured over thin, square-shaped, paper and plastic specimens; the specimens were oriented vertically and horizontally in a sealed combustion chamber. During weightlessness the profile of the flame was found to be rounded or dome-shaped for either orientation while the flame spread in a uniform circular pattern over the specimen surface. Flame spread rates were lower in zero gravity than in normal gravity.

INTRODUCTION

The fire hazards associated with oxygen-rich atmospheres are well known. In a pure oxygen atmosphere, most solid materials burn at a faster rate and with a hotter flame than in a standard air atmosphere (ref. 1). In fact, some materials which are not readily combustible in air burn very rapidly in 100-percent oxygen (ref. 2). Accidental fires occurring in oxygen-rich atmospheres are usually flash-type events starting and spreading in a matter of seconds and leading to very damaging and serious results.

Various studies have been made in an effort to reduce these fire hazards. The effects of nitrogen, helium, and other inert gas diluents are reported in references 3 to 6. In general, helium is better than nitrogen for reducing the risk of ignition but worse for opposing convective spread (ref. 7). NASA is continuously conducting industry searches for newly developed materials with fire-resistant properties usable for spacecraft application. A description of the program under which these new materials are tested and evaluated is given in reference 8.

Since the Apollo accident in 1967, most materials in the spacecraft have been reselected for their noncombustible characteristics and relocated to minimize flame propagation. In spite of these modifications, combustion of some materials is still possible. Most of the present literature on combustion pertains to burning in normal-gravity environments. However, during the greater part of the Apollo mission the spacecraft is in zero gravity, and knowledge of flame propagation characteristics in a zero-gravity environment is highly desirable. Literature in this area is not very abundant. Experimental results have been obtained by Kimzey (refs. 9 and 10) who photographed burning, solid, tubular-shaped, fuel specimens while they were exposed to weightlessness; the weightless environment was obtained in aircraft flying parabolic trajectory patterns. The flame that resulted, in zero gravity, had a spherical or dome-shaped corona, became progressively darker and smaller, and appeared to extinguish itself in some cases. Further findings indicate that ignition temperatures were of the same order of magnitude as in normal gravity.

This report presents the results of a study conducted in the Lewis Research Center's 2.2-Second Zero-Gravity Facility. Thin, square, specimens of paper and plastic material were ignited at their centers and burned in both vertical and horizontal orientations in a sealed combustion chamber. Flame spread rate was the main characteristic measured and compared in normal and zero gravity; other properties, such as flame profile, spread pattern, and color, were also observed.

APPARATUS AND PROCEDURE

Test Facility

The facility in which the tests were performed was a drop tower which provides a maximum of 2.2 seconds of weightlessness. The basic principle of operation is that a a test package free falls within an air drag shield and as a result is subjected to an environment of less than 10^{-5} g's. Initially, the package is positioned inside the drag shield and both are suspended from the top of the tower by a wire; cutting the wire simultaneously releases both objects to start zero gravity. After the free fall distance is traversed, the package and shield are decelerated by falling into a sand chamber. A detailed description of the facility is given in the appendix.

Test Equipment

The test package is shown in figure 1 and consists of a combustion chamber, a high-speed camera, an electrical control system, and a battery power source.

The cylindrically shaped combustion chamber 30.5 centimeters (1 ft) in diameter and 61 centimeters (2 ft) high was made of stainless steel and had an internal volume of approximately 445×10^2 cubic centimeters (1.57 ft^3). Four ports equidistant around the chamber were available for installing and observing the materials under test. Other features of the chamber included a vacuum control valve, an oxygen fill valve, and a 6.9-newton-per-square-centimeter-gage (10-psig) relief valve. The test specimen was held in place by a specimen holder mounted to the base of the combustion chamber. A mirror attached to the rear flange of the chamber and positioned over the holder provided a top view of the burning material. Both vertical and horizontal specimen holders are shown in figure 2 in their approximate positions relative to the top-view mirror. The test materials were clamped between two pieces of blued-steel shim stock which resulted in a square burning area of 6.3 centimeters (2.5 in.) on each side. Also shown in the figure is the nichrome ribbon igniter which was operated by two time-delay relays and a dc battery. Ignition was obtained by contact of the wire with the specimen.

The 16-millimeter high-speed camera was operated at approximately 400 frames per second using Ektachrome EF type 7242 color film. A digital clock accurate to 0.01 second was always in view of the camera lens. Also included in the test package was the power source consisting of four 15-volt dc batteries and the electrical control system containing various switches and relays needed to control the sequence of events.

Specimen Materials

Five materials were used in the tests; two specimens were made of plastic and the remaining three were paper. High burning rate materials were selected because of the minimum available test time in zero gravity. Preliminary tests had shown that thin paper and plastic specimens would ignite rapidly and burn with a reasonably steady flame which could be analyzed on a film projector. The materials were ignited at their geometric centers to eliminate edge effects as reported by Huggett in reference 2. There was no special cleaning or preparation of the materials before each test.

The plastics (cellulose acetate; Fed. Spec. LP504) were nonhydroscopic shim stock supplied by the Artus Manufacturing Co., Englewood, New Jersey. Thicknesses were 0.025 and 0.051 millimeter.

Two of the papers, Japanese tissue and Silkspan, are commonly used by hobbyists as model airplane coverings. The Silkspan, type 00, was 0.05 millimeter thick; and manufactured by K and S Engineering, Chicago, Illinois; it was made of Manila hemp and various cellulosic fibers. The Japanese tissue was 0.03-millimeter thick and was distributed by the SIG Manufacturing Co., Inc., Montezuma, Iowa. The tissue had a smoother appearing surface than Silkspan, but the latter had a more uniform texture when viewed under a microscope. The third paper, commonly used in typewriters, was white bond paper, type III, containing 25-percent rag; its thickness was 0.10 millimeter and it is manufactured by Allied Paper, Inc., Kalamazoo, Michigan.

Procedure

Prior to each test, the combustion chamber was vacuumed and wiped clean of any residue left from the previous run. The material was then clamped in the specimen holder and adjusted to slightly contact the igniter wire and the complete assembly was installed in the chamber. The combustion chamber was then sealed and pumped down by means of an air aspirator to approximately 0.55 newton per square centimeter absolute (0.80 psia). The chamber was then cycled through a pressurizing and depressurizing process twice with oxygen (nominally 99.6 percent pure) to 10.3 and 0.55 newtons per square centimeter absolute (15 and 0.80 psia), respectively, and finally brought to its operating pressure of 3.45 newtons per square centimeter absolute (5 psia). The package was then placed in the drag shield in preparation for the drop.

The igniter was timed to operate 0.6 second after the start of zero gravity and remain on for approximately 0.5 second during the drop.

Flame spread rates were obtained by measuring the displacement of the flame front from the center, or ignition point, of the material as a function of time. The measurements were made on the outermost visible edge of the flame, which usually appeared as a light-blue fringe area, as the flame traveled across the specimen. Where possible, these measurements were taken on four directions of flame travel, that is, the left edge as it spread in a leftward direction from the center, the upper edge in an upward direction, the lower edge in a downward direction, and the right edge traveling to the right of the specimen center. Displacement-against-time curves were then drawn and their slopes calculated to obtain the average flame spread rates. The estimated error involved in measuring the displacements was ±0.05 centimeter, which resulted in a maximum error in the burning rates of 3 percent.

RESULTS AND DISCUSSION

General Observations

Ignition. - There were no observable differences between ignition in zero gravity and in normal gravity. Usually, ignition occurred with a slight amount of smoke followed by a flash and then either a partial dimming or a complete disappearance of the flash. An instant later, a flame became established and began to spread across the material. This description was typical of all materials burned in both orientations. The plastic materials seemed to produce more smoke than the papers before the flash occurred.

Flame spread pattern and profile. - In figure 3(a), a vertically oriented specimen is shown burning during zero gravity. Ignition occurs as a flash in the first photograph; the flash disappears after 0.015 second as seen in the second photograph. Although the clock indicated 0.745 second at ignition, it must be noted that the clock starts at the instant zero gravity starts. At 0.1 second after ignition, the flame has established itself and is seen spreading in a uniform circular pattern across the front surface of the material. The circular spreading continues until at 0.5 second the flame is seen after it has reached the specimen holder. At 0.7 second burning continues but the flame is getting less intense; the material can also be seen starting to wrinkle or crease. At 1.2 seconds, it appears that the flame has extinguished itself except for a few hot spots around the specimen holder; but at the instant deceleration occurs, a flame outlining a small amount of unburned material is shown in the last photograph. In a repeated test with the same substance, hardly any of the material was left unburned. For comparative purposes, figure 3(b) shows the same material burning in normal gravity. A typical normal gravity convective pattern is seen in the last two photographs of this figure.

The profile of a flame spreading over a vertical specimen in zero gravity can be seen in the top view in figure 4; it appears rounded or dome-shaped, somewhat similar to the results reported by Kimzey in reference 9. A complete view of the profile is seen more clearly in figure 5, which shows a horizontally oriented plastic specimen burning in zero gravity (a), and normal gravity (b). The profile view for the zero-gravity case shows the flame spreading in a somewhat flattened hemispherical shape, while the top view seen in the mirror shows the uniform circular spread pattern. In the last photograph of figure 5(b) for the normal-gravity case, the flame spreading on the bottom surface of the horizontal specimen is slightly ahead of the flame on the top surface.

Color. - In general, the overall color intensity of the flames appeared to be brighter in normal gravity than in zero gravity; the burning seemed to be less violent in zero gravity. Usually, the interiors of the flames were yellow in color surrounded on the outside by a bluish fringe zone. In some cases, the fringe zone was hardly visible in zero gravity; whereas, in normal gravity it was very definitely defined in shape and color. One exception was the plastics which seemed to burn so intensely in normal gravity that the interior of the flame appeared almost white and no fringe zone was visible; during zero gravity, a faint reddish-orange fringe area was present.

Flame Spread Rate

Vertical orientations. - Table I(a) lists the average flame spread rates in four directions of travel on a vertical orientated specimen burning in zero gravity. The results are averages of two, and in some cases three, identical tests; the deviation from the average values was never greater than 10 percent, and this maximum occurred only in the data for the 0.051-millimeter plastic. The data indicated that for a particular material burning in zero gravity the average flame spread rate in all directions of travel is essentially the same.

Table I(b) lists the normal gravity results. In this case, the top edge of the flame, moving in an upward direction from the center of the specimen, traveled so fast that it could not be accurately measured on the film. Thus, only the displacement of the side edges and lower edge of the flame front were measured; the resulting values indicate that the base of the flame moved in a downward direction slightly slower than the spreading in the side directions. Also, as was expected, both side edges of the flame front traveled uniformly away from the center at approximately the same rate.

Horizontal orientations. - A compilation of the flame spread rate of horizontal orientated specimens burning in both zero and normal gravity is given in table II. Displacement data were taken of the flame as it traveled across the top surface of the material only, and since all measurements were made in the front view and none in the mirror view, only the side edges of the moving flame front were measured. Again, as was expected, the spread rate of both sides of the flame is essentially the same for a particular material burning in a specific gravity field. However, a difference in rates between normal and zero gravity can also be seen and is summarized and discussed in the following section of the report.

Normal- and zero-gravity comparison. - For a summarizing comparison of flame spread rates in normal and zero gravity, table III lists the complete results and the percentage difference between the rates in their different gravity environments. The listed results are averages of the raw data presented in tables I and II.

In the horizontal orientations, left- and right-edge burning rates, obtained from table II, were averaged together to obtain a representative value of flame spreading for this particular orientation in both gravity environments. As can be seen in the first three data columns of table III, the average flame spread rate is definitely lower for all the materials burning in zero gravity than for those burning in normal gravity; the percent decrease ranges from 8.2 percent for Japanese tissue to 35.7 percent for the 0.025-millimeter-thick plastic.

The next section of table III contains the results for the vertical orientations. First, the left- and right-edge data show that flame spread rate is again lower in zero gravity than in normal gravity for every material tested. The percentage decrease ranged from 14.7 percent for Silkspan to 47.8 percent for bond paper. It is of interest to note that, in general, the percent decreases in rates for the vertical orientations are slightly higher than those for the horizontal orientations. This result occurs because the side edges of the flame front spread faster in the vertical position than in the horizontal position during normal gravity; this is due to the effects of free convection on the burning processes which are different for the two orientations in normal gravity.

In the last three data columns of table III, the upper- and lower-edge spread rates are presented for the vertically orientated specimens. In general, the comparative results are the same as before; mainly, flame spread rate is lower in zero gravity than in normal gravity, ranging from 2.9 percent for Silkspan to 40 percent for bond paper. Note that the normal gravity column of values for these edges contains only the lower edge of travel of the base of the flame since the top edge could not be measured in normal gravity.

It can also be noted from table III, that during zero gravity the spread rate in the vertical orientation is essentially the same as the rate in the horizontal orientation. The lack of convection in zero gravity eliminates the effect of geometric orientation on flame spread rates for a given material burning in weightlessness.

Finally, an observation can be made concerning the approximation of zero gravity spread rates from normal gravity experiments. It might be expected by some investigators and was proposed by Huggett (ref. 2) that flame spread rate in a downward direction on a vertical surface or across the top of a horizontal surface in normal gravity would be applicable to zero gravity conditions. From table III, it can be seen that the normal gravity burning rates in both of these cases were comparatively the same, as observed by Huggett (ref. 2), but the zero gravity burning rates were consistently lower. Consequently, any application of normal gravity results to zero gravity conditions might prove to be significantly inaccurate.

SUMMARY OF EXPERIMENTAL RESULTS

An investigation was conducted to determine the difference between the burning of solids during weightlessness and normal gravity in a 3.45-N/cm^2 abs (5-psia) oxygen atmosphere. Various flame characteristics, such as profile, spread pattern, and color, were observed. Flame spread rates were measured and their values compared in normal and zero gravity. Several specimens of thin paper and plastic 6.3 centimeters (2.5 in.) square were ignited at their centers and burned in vertical and horizontal orientations in a sealed combustion chamber. The following results were obtained:

1. During weightlessness, the flame has a rounded or dome-shaped profile and spreads uniformly in a circular pattern across the surface of the material for either

orientation; as a result, the flame spread rates were similar in magnitude in all directions in the surface plane of the material.

2. For all materials tested, flame spread rates were lower in zero gravity than in normal gravity in both vertical and horizontal orientations. The magnitude of decrease ranged from 2.9 to 47.8 percent.

3. The normal-gravity measurements of flame spread rate across the top surface of a horizontally oriented specimen and in a downward direction of a vertically oriented specimen were essentially the same; however, these particular measurements were greater than the zero-gravity measurements and did not provide a good approximation to the zero-gravity flame spread rates.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, January 14, 1970,
124-08.

APPENDIX - TEST FACILITY

The experimental data for this study were obtained in the Lewis Research Center's 2.2-Second Zero-Gravity Facility. A schematic diagram of this facility is shown in figure 6. The facility consists of a building 6.4 meters (21 ft) square by 30.5 meters (100 ft) tall. Contained within the building is a drop area 27 meters (89 ft) long with a cross section 1.5 by 2.75 meters (5 by 9 ft).

Mode of Operation

A 2.2-second period of weightlessness is obtained by allowing the experiment package to free fall from the top of the drop area. In order to minimize drag on the experiment package, it is enclosed in a drag shield, designed with a high ratio of weight to frontal area and low drag coefficient. The relative motion of the experiment package with respect to the drag shield during a test is shown in figure 7. Throughout the test the experiment package and drag shield fall freely and independently of each other; that is, no guide wires, electrical lines, etc., are connected to either. Therefore, the only force acting on the freely falling experiment package is the air drag associated with the relative motion of the package within the enclosure of the drag shield. This air drag results in an equivalent gravitational acceleration acting on the experiment which is estimated to be below 10^{-5} g's.

Release System

The experimental package, installed within the drag shield, is suspended at the top of the drop area by means of a highly stressed music wire attached to the release system. This release system consists of a double-acting air cylinder with a hard-steel knife edge attached to the piston. Pressurization of the air cylinder drives the knife edge against the wire which is backed by an anvil. The resulting notch causes the wire to fail, smoothly releasing the experiment. No measurable disturbances are imparted to the package by this release procedure.

Recovery System

After the experiment package and drag shield have traversed the total length of the drop area, they are recovered by decelerating in a 2.2-meter- (7-ft-) deep container filled with sand. The deceleration rate (averaging 15 g's) is controlled by selectively varying the tips of the deceleration spikes mounted on the bottom of the drag shield (fig. 6). At the time of impact of the drag shield in the deceleration container, the experiment package has traversed the vertical distance within the drag shield (compare figs. 7(a) and (c)).

Procedure for Test Drop

Electrical timers on the experiment package are set to control the initiation and duration of all functions programmed during the drop. The experiment package is then balanced and positioned within the prebalanced drag shield. The wire support is attached to the experiment package through an access hole in the shield (see fig. 7(a)). Properly sized spike tips are installed on the drag shield. Then the drag shield, with the experiment package inside, is hoisted to the predrop position at the top of the facility (fig. 6) and connected to an external electrical power source. The wire support is attached to the release system and the entire assembly is suspended from the wire. After final electrical checks and switching to internal power, the system is released. After completion of the test, the experiment package and drag shield are returned to the preparation area.

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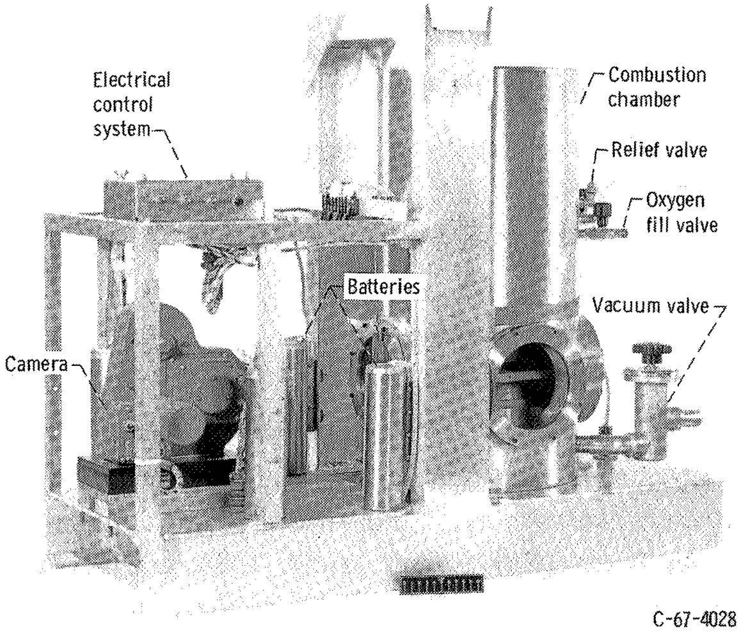
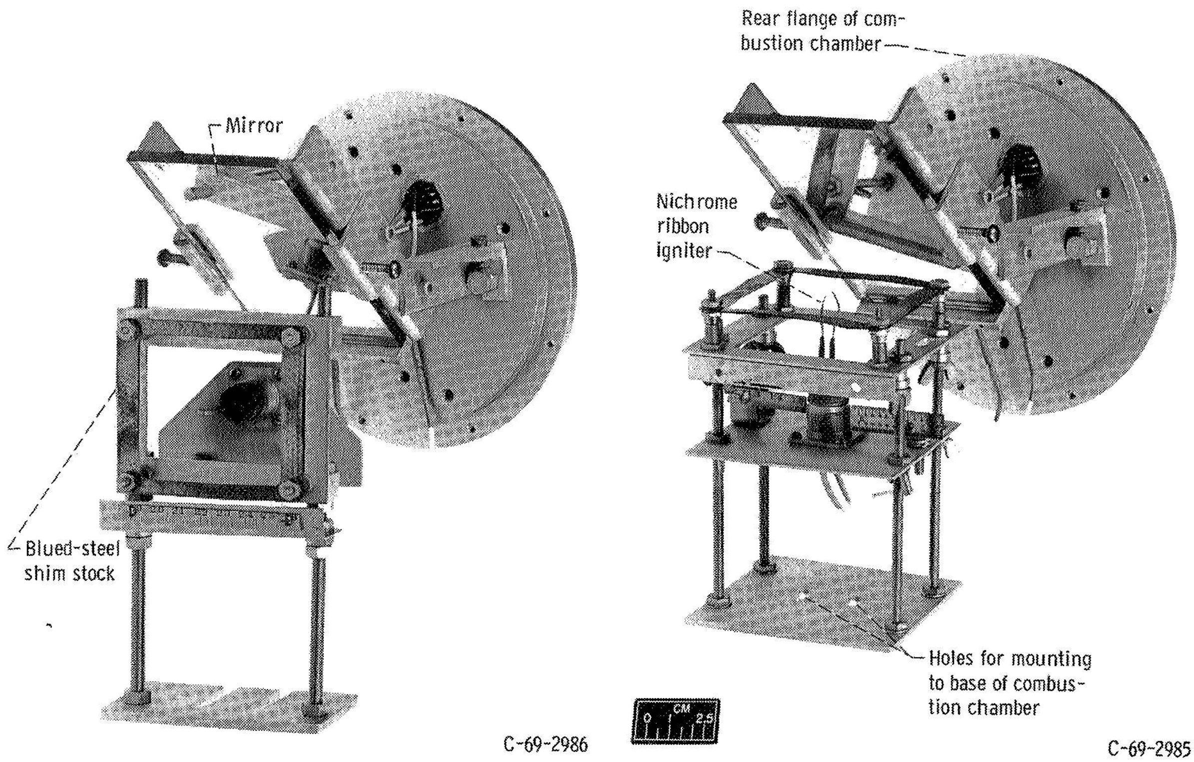


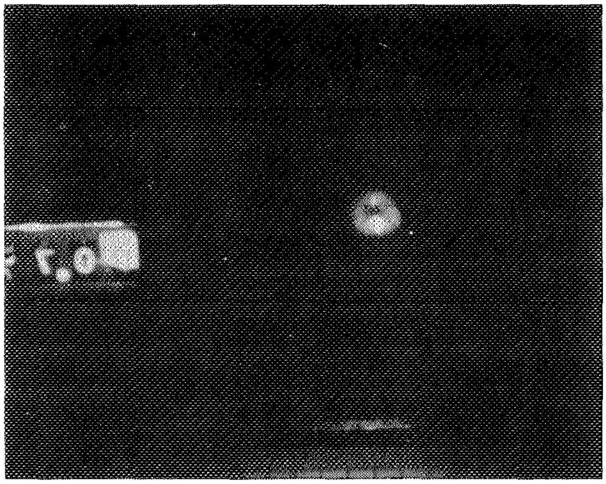
Figure 1. - Test package.



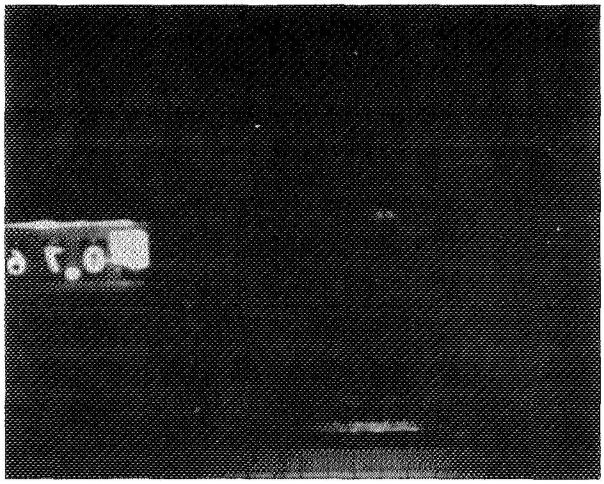
(a) Specimen holder for vertical orientation.

(b) Specimen holder for horizontal orientation.

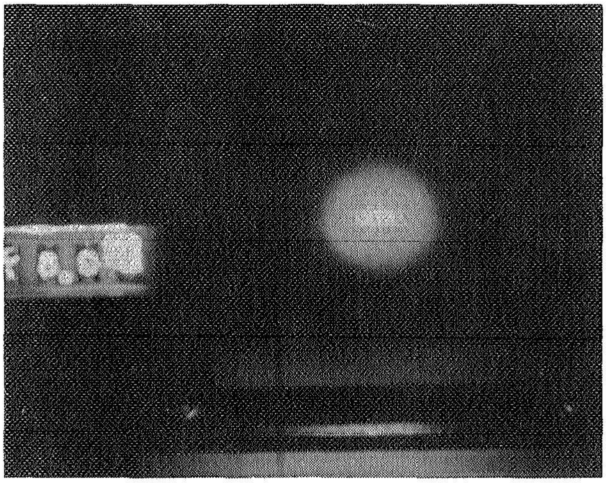
Figure 2. - Specimen holders.



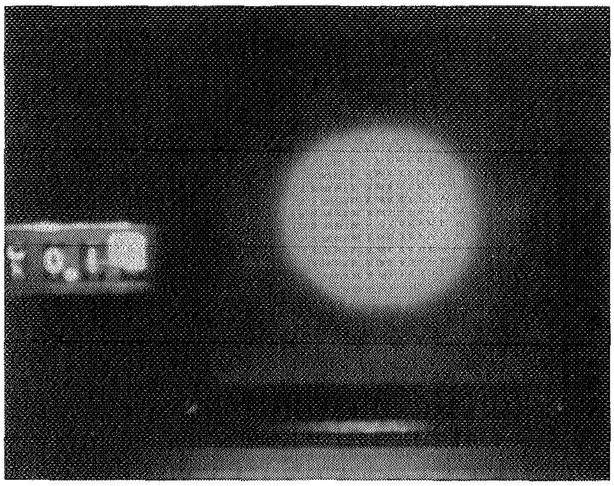
0 Second; ignition.



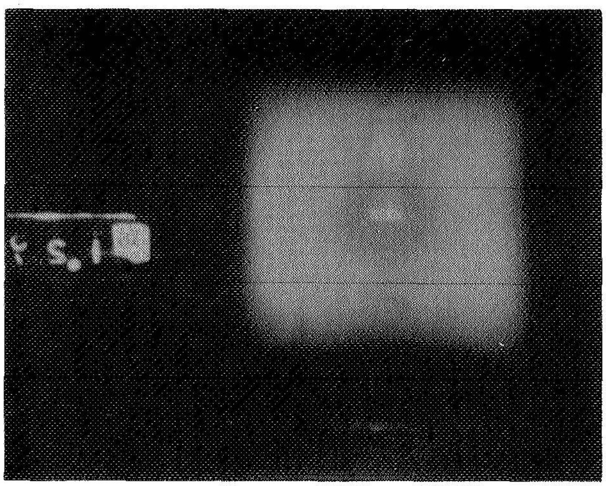
0.015 Second; flame grows dimmer immediately after ignition.



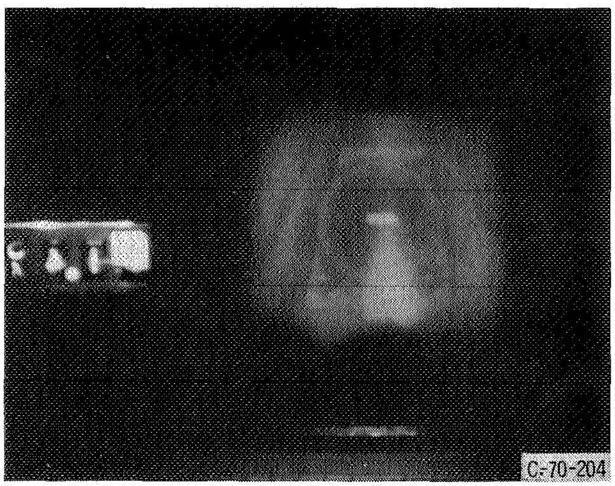
0.1 Second; flame spreading uniformly in a circular pattern.



0.3 Second; flame continues to spread uniformly.



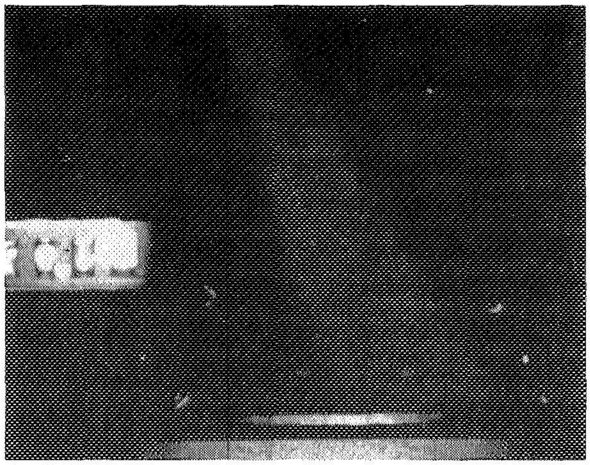
0.5 Second; flame has reached specimen holder and is growing dimmer.



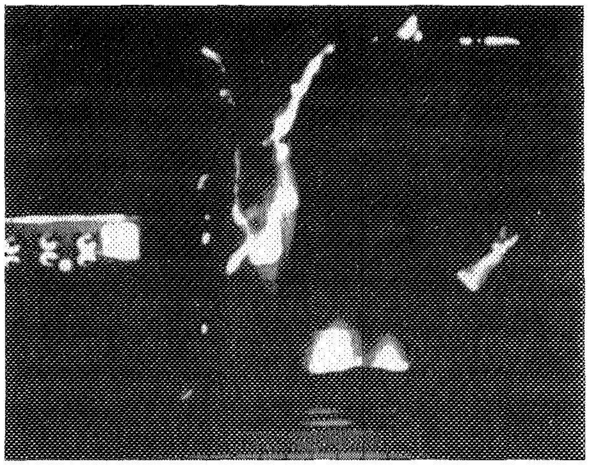
0.7 Second; flame continues to grow dimmer.

(a) Zero gravity.

Figure 3. - Burning of Japanese tissue; vertical orientation.

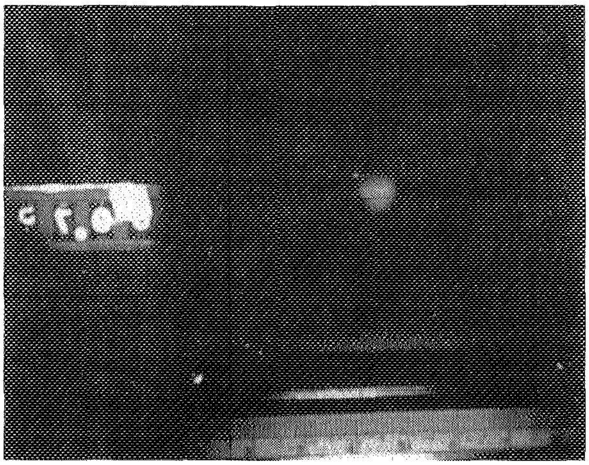


1.2 Second; flame appears extinguished except for a few hot spots.

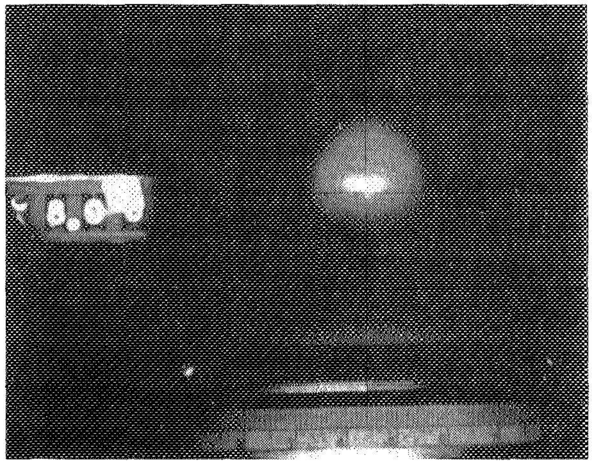


End of weightlessness; flame reappears outlining some unburned material.

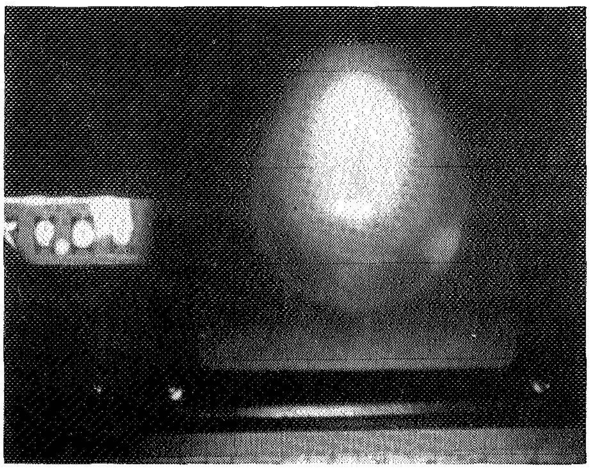
(a) Continued. Zero gravity.



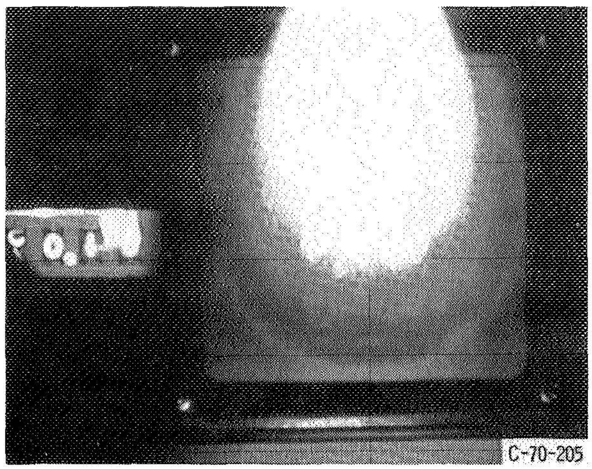
0 Second; ignition.



0.1 Second; flame begins spreading.



0.2 Second; typical normal-gravity flame pattern.



0.3 Second; flame reaches specimen holder.

(b) Normal gravity.

Figure 3. - Concluded.

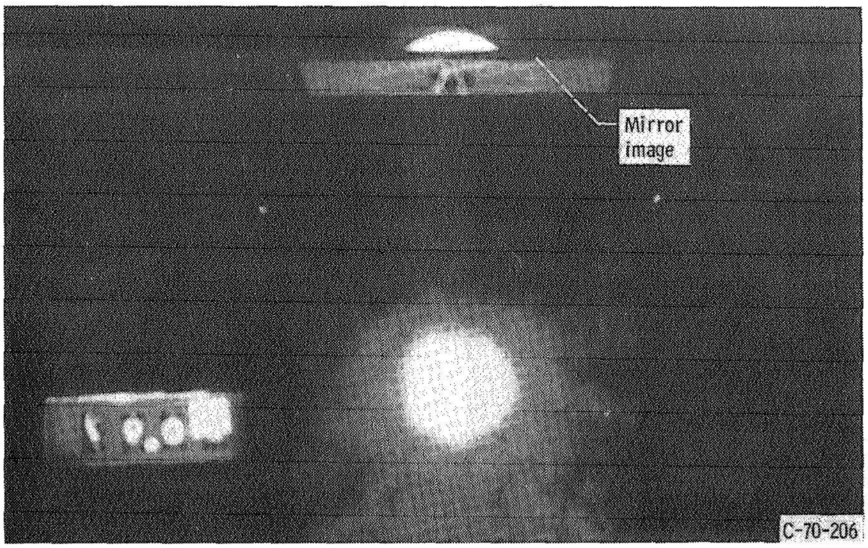
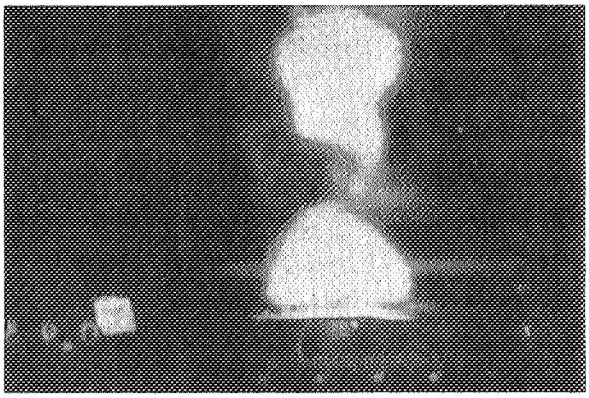
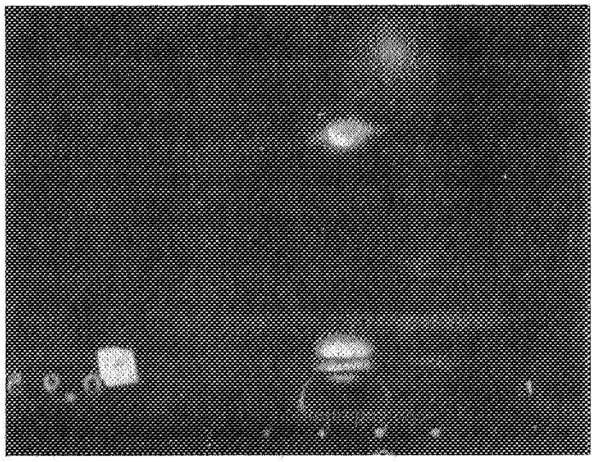


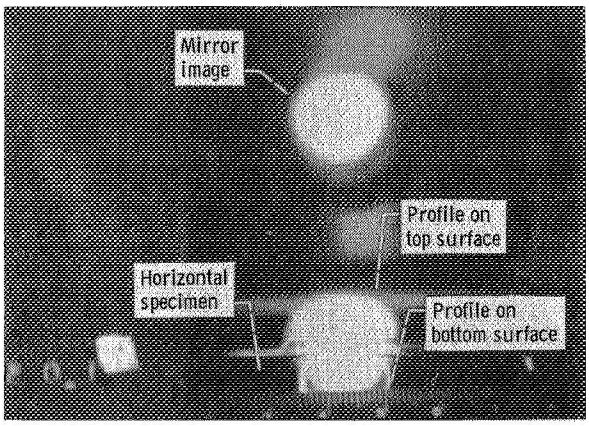
Figure 4. - Burning of Silkspan in zero gravity. Vertical orientation; flame profile appears dome-shaped in top view as seen in the mirror.



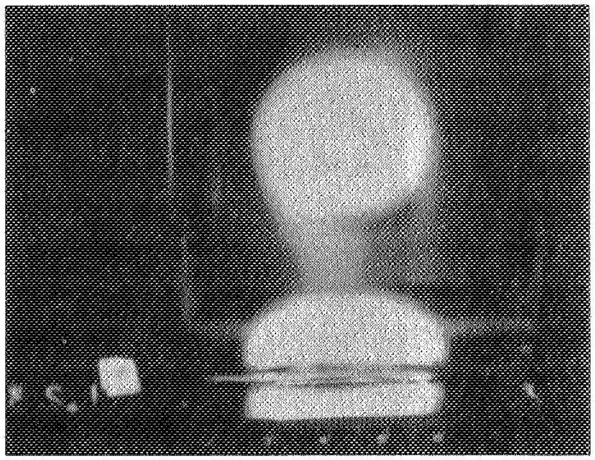
0 Second; ignition.



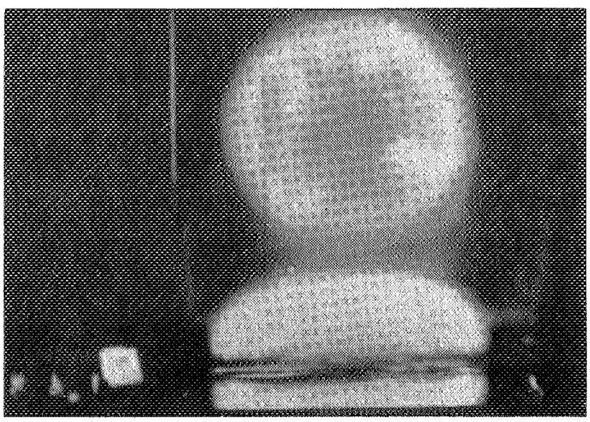
0.02 Second; flame gets smaller immediately after ignition.



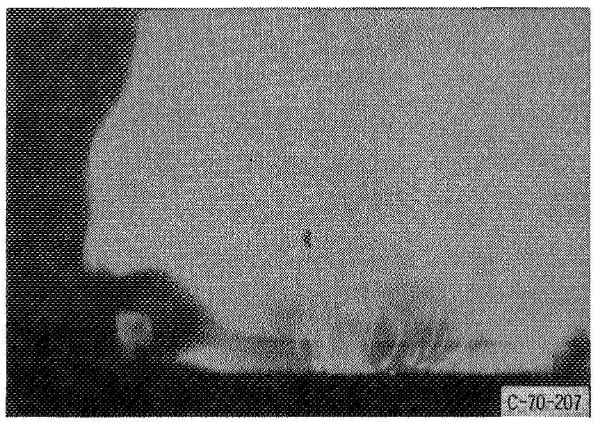
0.1 Second; flame spreads uniformly.



0.3 Second; flame continues to spread uniformly.



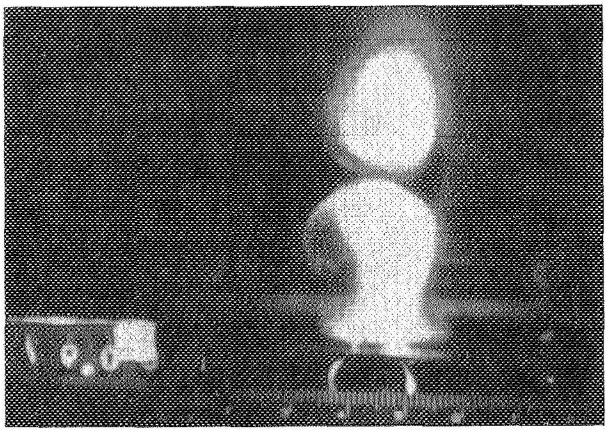
0.5 Second; flame continues to spread uniformly.



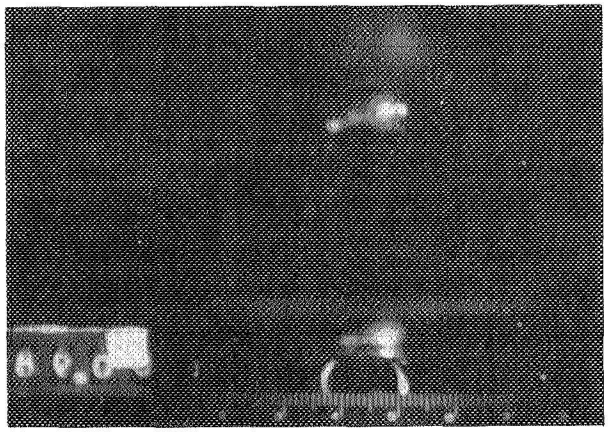
End of weightlessness; package is decelerating into sand.

(a) Zero gravity.

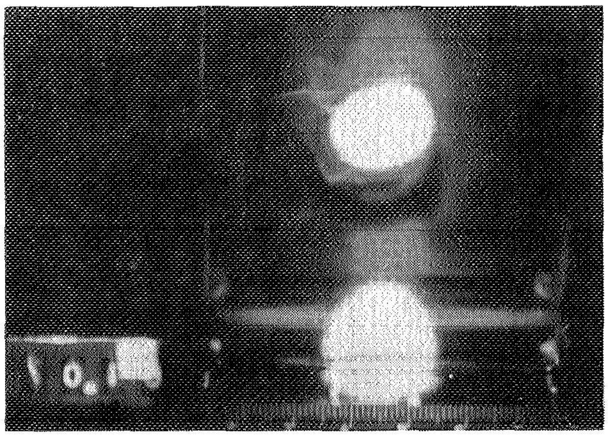
Figure 5. - Burning of 0.025-millimeter-thick plastic shim stock; horizontal orientation.



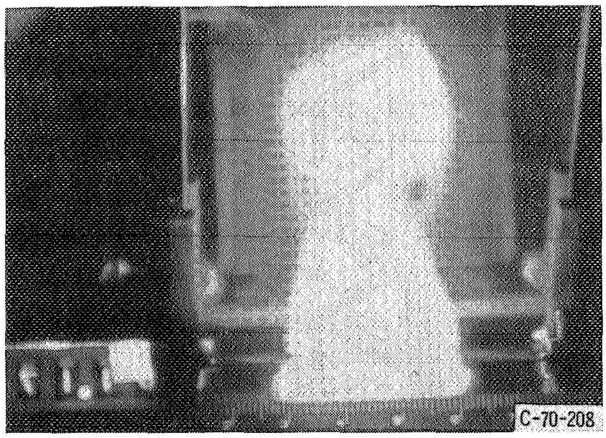
0 Second; ignition.



0.01 Second; flame gets smaller immediately after ignition.



0.1 Second; flame profile forming.



0.2 Second; typical normal-gravity flame profile.

(b) Normal gravity.

Figure 5. - Concluded.

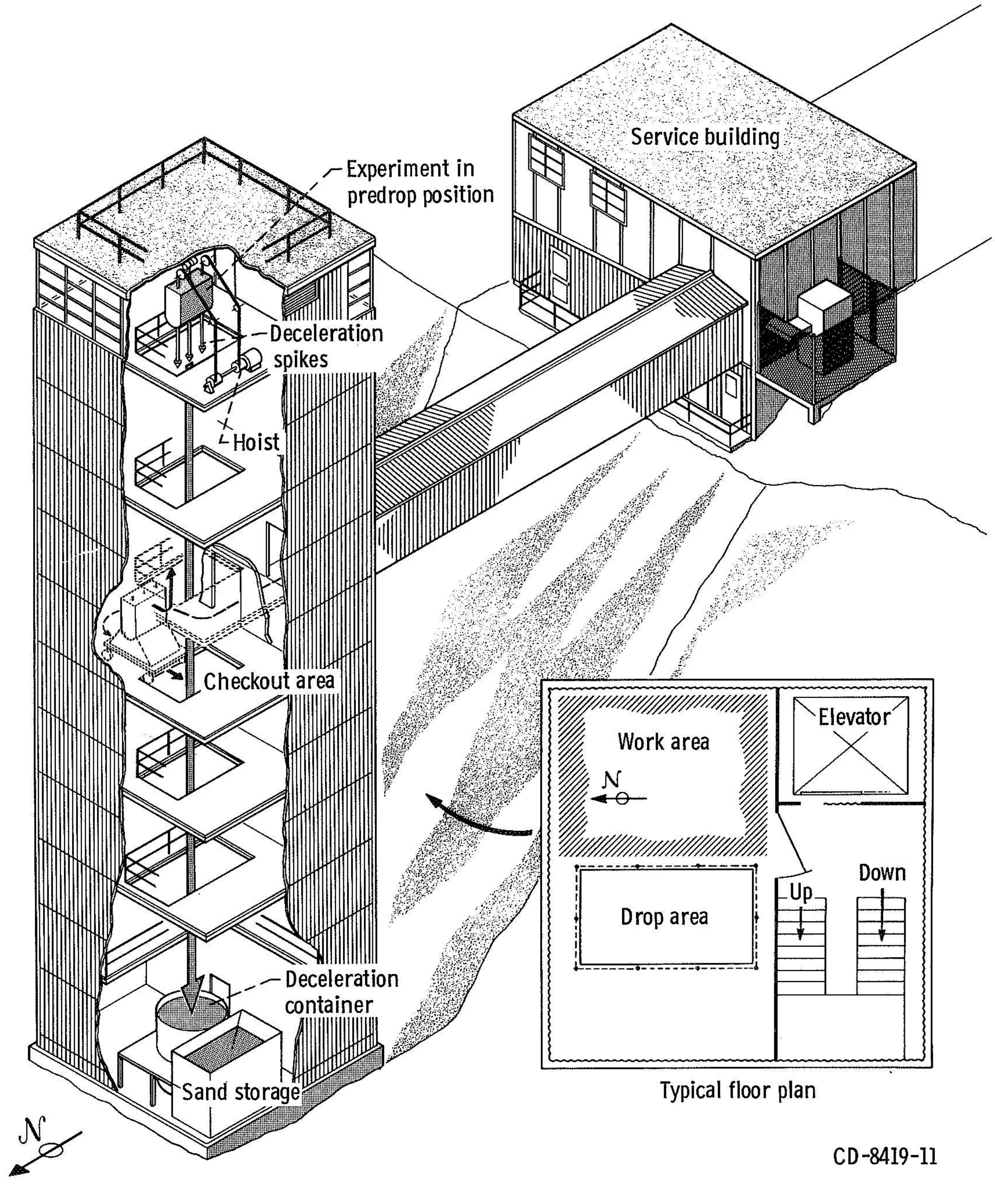


Figure 6. - 2.2-Second Zero-Gravity Facility.

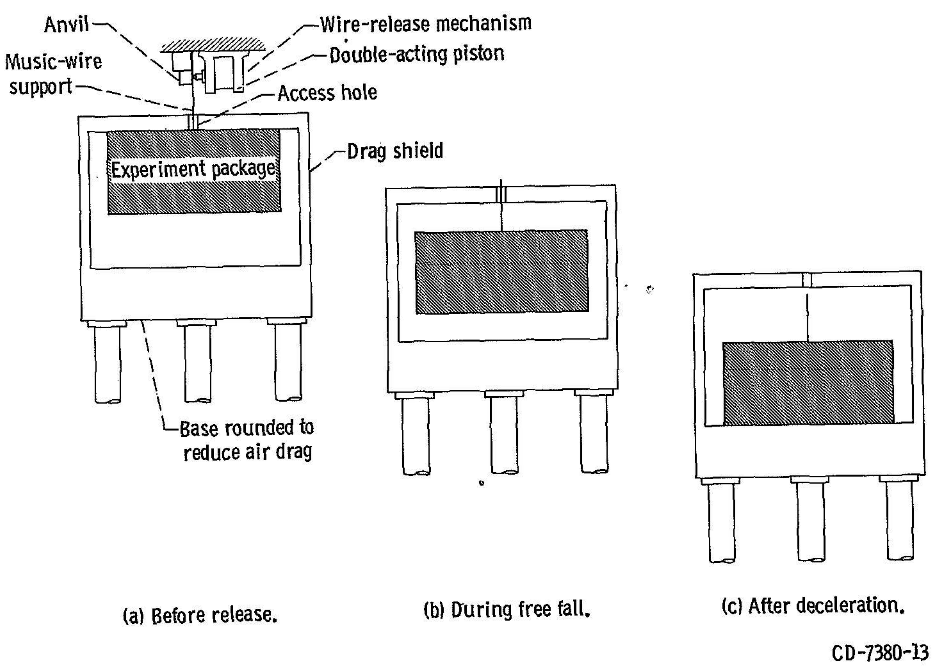


Figure 7. - Position of experiment package and drag shield before, during, and after test drop.

TABLE I. - FLAME SPREAD RATES,

VERTICAL ORIENTATION

(a) Zero gravity

Material	Left edge	Right edge	Upper edge	Lower edge
	Flame spread rates, cm/sec			
Silkspan	10.0	9.8	10.0	9.8
Japanese tissue	9.0	8.4	8.6	8.8
Plastic, 0.025 millimeter thick	4.2	4.3	4.4	4.3
Plastic, 0.051 millimeter thick	2.3	2.3	2.2	2.3
Bond paper	1.2	1.2	1.3	1.2

(b) Normal gravity

Material	Left edge	Right edge	Upper edge	Lower edge
Silkspan	11.8	11.4	----	10.2
Japanese tissue	10.7	10.6	----	9.8
Plastic, 0.025 millimeter thick	6.0	6.1	----	5.6
Plastic, 0.051 millimeter thick	3.5	3.5	----	3.2
Bond paper	2.3	2.3	----	2.0

TABLE II. - FLAME SPREAD RATE,

HORIZONTAL ORIENTATION

Material	Zero gravity		Normal gravity	
	Left edge	Right edge	Left edge	Right edge
	Flame spread rate, cm/sec			
Silkspan	9.2	9.4	10.6	10.4
Japanese tissue	9.2	8.9	10.0	9.6
Plastic, 0.025 millimeter thick	3.6	3.6	5.7	5.5
Plastic, 0.051 millimeter thick	2.2	2.2	3.0	3.0
Bond paper	1.5	1.5	2.0	2.0

TABLE III. - AVERAGE FLAME SPREAD RATES

Material	Horizontal orientation			Vertical orientation					
	Left and right edges			Left and right edges			Upper and lower edges		
	Flame spread rate, cm/sec		Percent decrease	Flame spread rate, cm/sec		Percent decrease	Flame spread rate, cm/sec		Percent decrease
	Normal gravity	Zero gravity		Normal gravity	Zero gravity		Normal gravity[a]	Zero gravity	
Silkspan	10.5	9.3	11.4	11.6	9.9	14.7	10.2	9.9	2.9
Japanese tissue	9.8	9.0	8.2	10.6	8.7	17.9	9.8	8.7	11.2
Plastic, 0.025 millimeter thick	5.6	3.6	35.7	6.0	4.2	30.0	5.6	4.3	23.2
Plastic, 0.051 millimeter thick	3.0	2.2	26.6	3.5	2.3	34.3	3.2	2.3	28.1
Bond paper	2.0	1.5	25.0	2.3	1.2	47.8	2.0	1.2	40.0

[a]The vertical-orientation, normal-gravity tests produced upper-edge spread rates that were much faster than those for the lower edge or either of the side edges. Therefore, only the lower-edge values obtained from table I were used as the average for comparison with the zero-gravity results.

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