1974 ?

FINAL REPORT

SKYLAB EXPERIMENT M-479, ZERO GRAVITY FLAMMABILITY

J. H. Kimzey
Principal Investigator

National Aeronautics and Space Administration
LYNDON B. JOHNSON SPACE CENTER
Houston, Texas

SKYLAB EXPERIMENT M-479

ZERO GRAVITY FLAMMABILITY

BY

J. H. Kimzey

Lyndon B. Johnson Space Center

Houston, Texas 77058

ABSTRACT

Flammability under conditions of weightlessness was investigated in Skylab 4. Thirty-seven experiments using six materials were successfully carried out to learn how a flame acts in the absence of convection. Specific objectives were to measure the extent of surface flame propagation and flash-over to adjacent materials, rates of surface and bulk flame propagation, self-extinguishment, and extinguishment by both vacuum and water spray. Data were returned in the form of crew comments on voice tapes and sixteen millimeter motion pictures taken at 24 frames per second. All experiments were performed and all hardware functioned properly, although an operational oversight caused the water in the supply tank to be less than the minimum required pressure. Burning rates were significantly reduced as anticipated from earlier aircraft tests. Some reduction of total burning was also noted. The surface burn was not followed by continued inward burning as typically experienced on Earth although some one-g tests at extremely low pressures have partially reproduced this condition. Ignition and extinguishment also appear to be similar to one-g. A soft blue flame was seen by the crew, but was not detected on the film emulsions used. Smoke patterns were also noted.

SKYLAB EXPERIMENT M-479
ZERO GRAVITY FLAMMABILITY

INTRODUCTION

Knowledge of flammability in the one-g (unit-gravity) Earth environment is very comprehensive even though it is far from complete. In spacecraft which experience weightlessness (zero-g) for extended periods of time, the resultant lack of convection introduces many complicating factors in understanding the various phases of combustion. Experience with short-term weightlessness was obtained with aircraft. These results led to the development of Experiment M-479 in order that more detailed data of ignition, propagation, and extinguishment during zero-g might be gained. In the final configuration, experiment M-479 was one of many experiments using the Manufacturing in Space Facility, M-512. The tests were carried out in the Earth orbit by Lieutenant Colonel Gerald Carr, USMC, Commander of Skylab, SL-4, February 4 and 5, 1974.

BACKGROUND

An investigation of flammability under conditions of weightlessness began over 10 years ago. These early tests with aircraft showed that without convection a flame has a somewhat spherical corona as seen on the right, figure 1. In such a case, the fuel is surrounded by a corona which isolates the material from the surrounding atmosphere rather than extending above the fuel as noted on the left. Hardware for these aircraft tests was very basic consisting of a 10-inch diameter chamber in which the fuel was positioned. A motion picture camera recorded ignition and burning (figure 2). Fuels were selected to represent a variety of recorded materials with various melting points and flammability characteristics (figure 3).

AIRCRAFT TESTS

Details of the aircraft studies of flammability under zero-g have been reported (refs. 1-4). Zero-g times varied from 4 to 10 seconds. Burning rates from this series of test were measured (figure 4) for some materials. Conclusions from these tests are given in figure 5.

SKYLAB TESTS

An experiment was originally prepared in September 1966 to explore several unique features of a flame in zero-g. Later, approval was granted for Experiment M-479 to be part of the Apollo Applications Program as documented in the Experiment Implementation Plan, dated October 10, 1967 (ref. 5). As such, 100 tests of 12 different materials were planned. The objectives were more extensive than the final version in that they included extinguishment by helium as well as water and vacuum, both zero convection and forced convection, flame spectra analysis, and the analysis of combustion products.

Over the next few years, the details of M-479 were finalized and documented in the Experiment Requirements Document (ERD) for Zero-Gravity Flammability (Experiment M-479) of January 20, 1970, amended (ref. 6). As such, 37 tests of six different nonmetallic materials were specified. Other appropriate documentation was prepared, designs were submitted and tested, hardware was built, and qualification testing was completed. The hardware was installed in SL-1 and was launched April 30, 1973.

OBJECTIVES

The objective of M-479 were to determine:

a. Extent of surface flame propagation, flash-over to adjacent materials, etc.

b. Rates of surface and bulk flame propagation under zero convection.

c. Self-extinguishment.

d. Extinguishment by vacuum or water spray.

These are restated as "functional objectives" in the Mission Requirements Document, "Third Skylab Mission" SL-4 of August 27, 1973, I-MRD-001F, Volume III (ref. 7) and are listed below:

FO 1 - Perform 12 test cycles of undisturbed burning through burnout on 6 specimens types (tests 1 through 12).

FO 2 - Perform 6 test cycles of undisturbed burning with a vacuum quench of 6 specimen types (tests 13 through 18).

FO 3 - Perform 6 test cycles of undisturbed burning with a water spray quench on 6 specimen types (tests 19 through 24).

FO 4 - Perform 6 test cycles of undisturbed burning of partially supported specimens on 6 specimen types (tests 25 through 30).

FO 5 - Perform 7 test cycles on 2 identical test specimens separated by several different material gap distances (tests 31 through 37).

FUELS

Material selected for burning was severely limited by the fact that only a few tests were available and several objectives had to be met. Criteria for selection included safety to the crew, applicability to future spacecraft designs, stability over long period in an oxygen-rich atmosphere, and low toxicity of combustion products as well as materials which cover a wide spectrum of flammability from the standpoint of both ignition and burning rates. The resultant fuels and corresponding test numbers are listed below.

FUEL	SIZE, inches	TEST NUMBER	MASS, gm
Aluminized Mylar	2 5/8" x 3 5/8" x .0003"	1,7,13,19,25	0.0527 0.0514
Nylon Sheet	1" x 1" x .125"	2,8,14,20,26	2.9909 2.8508
Neoprene Coated Nylon Fabric	2 5/8" x 3 5/8"	3,9,15,21,27	1.3850 1.3665
Polyurethane Foam	1/4" x 1/4" x 2"	4,10,16,22,28	0.0636
Bleached Cellulose Paper	2 5/8" x 3 5/8" x .009"	5,11,17,23,29	0.4832 0.4444
Teflon Fabric	2 5/8" x 3 5/8"	6,12,18,24,30	1.5608
Paper, Two Pieces, Mounted in Parallel Face to Face Position With a Gap of 1/8", 1/4", 1/2"	2 5/8" x 3 5/8" x .009"	31 through 37	

The configuration of specimens 25, 27, 29, and 30 was slightly different as the materials had a series of 19 uniform parallel creases at 4 mm intervals which were formed at 90 degree angles giving a corrugation effect. This reduced the flat width of those specimens from 3 3/8" to the same 2 5/8" as the other mounted specimens. A silastic adhesive (Dow Corning Silastic 140 RTV) was used to attach the aluminized mylar, fabric, and paper to the supporting frame.

After testing, the return of specimens 2 and 8 was scheduled. The crew actually returned specimens 2, 8, 11, and 26 for post-test examination.

Specimens weights are given for the material alone. No adhesive, fittings or support frame are included in the values. In general, the lower weight applies to supported specimens except that the opposite is true for the sheet nylon.

HARDWARE

The "Materials Processing in Space Facility," figure 6, included the Flammability Specimen Container, Control Panel, Water Quench equipment, Vent Line, Work Chamber, and Accessories Container. This hardware was mounted in the Multi-Docking Adapter (MDA). A brief description of each follows:

Flammability Specimen Container - The 37 specimens were individually mounted under numbered metal covers in the Specimen Container. Each specimen included an electric connector with a resistance wire coil (32 gage Nichrome) in contact with the fuel which was mounted on a frame. A metal tab with the specimen number was positioned on the sample for recording by the camera. Each specimen was packaged to withstand the launch loads and vibration in order to be functional later in the mission.

Control Panel - Appropriate electrical controls were mounted in the control panel together with a pressure gage.

Water Quench Equipment - Means to deliver two ounces of water as a light spray for each of the six tests designated was provided. Preparation involved connecting a 60-foot umbilical hose to an onboard water tank which provided water. A nozzle assembly was provided.

Vent Line - Means to vent smoke overboard and to evaluate a vacuum quench extinguishment systems was provided by the vent line which was equipped with two valves. The line was 4" in diameter. A 1" screened orifice was provided to retard the vent rate and to filter out gross contamination generated by the experiments.

Work Chamber - The flammability tests were performed inside a spherical chamber having a volume of approximately 1.45 cubic feet. The chamber has a work light, electrical connections for ignition, a camera port with an exterior bracket for mounting the data acquisition camera (DAC), a bulkhead vent valve for admitting air into the camber from the MDA, plumbing connections for water and vent, and a hinged cover fitted with a large window (see figure 7).

Accessories - Several items were stored in the accessories container. This included the water nozzles, the water connection cover, the three interior cover glasses designed to shield the three ports (viewport, camera port, and work light port)from debris, the flammability specimen holder, the camera mirror, the heat sink cover, and two work chamber vent filters (screens).

Data Acquisition Camera (DAC) - A 16 mm motion picture camera was provided for major data recording. The camera was fitted with an 18 mm lens for this experiment and a mirror to take care of the angle of the bracket. This mirror, of course, gave a reverse image for the tests. Film included a 400-foot roll of color-infrared (Eastman #3443), interior color film (SO-168), and exterior color (SO-368). Camera settings were: 24 frames per second, shutter speed 1/60 second, focal length 13.426" and f-stop 2.8.

PROCEDURE

Experiment M-479 was scheduled for Day 81 of Skylab Mission SL-4. Commander Gerald Carr spent most of that day (February 4, 1974) on the experiment, including some voluntary overtime after the evening meal of Day 81 in an attempt to perform as many tests as possible. Most of the equipment was found to be fully functional. However, the water quench system was not delivering water. Video taping of post-test specimen number 2, nylon, was made as scheduled. Additional video taping included tests 16 and 17. This tape was dumped and viewed on the ground of Day 82 on which a total of 30 tests were carried out. In addition, Commander Carr continued work on the experiment during the late hours on Day 82, completing all 37 tests. The procedure was followed in voice recorded crew comments during the testing and, by means of a check list log, details immediately after testing were also recorded. One in-flight procedural change was to request a total of three ignition attempts, if possible, should the initial attempt fail to provide a flame. Another procedural change was to schedule all tests in numerical order. As originally planned, those tests using water were scheduled last to simplify cleanup.

RESULTS

All 37 tests were carried out over a period of 2 days; days 81 and 82. Voice recorder time intervals concerning M-479 are given in figure 8. Problems with the ignition of nylon, specimen number 2, caused a request for direction. The crew was told that three attempts should be made if possible. Other problems included ignition of the Teflon fabric which apparently burned away from the igniter wire and self-extinguished. Repeated attempts at ignition were unsuccessful. The experiment used ambient MDA air. As noted during Day 81, this turned out to be 65% oxygen at a pressure of 5.2 psia, giving insufficient oxygen for sustained burning of the Teflon fabric.

SPECIMENS

Four post-test specimens were returned. These were numbers 2, 8, 11, and 26. See figures 9 through 14. Three of these were nylon. The other, number 11, was paper.

Aluminized Mylar - Specimens ignited in each of the five tests. In test number 1 the flame traveled the entire length but did not cover the full width. Tests numbers 7 and 25 also burned the entire length but fuel in tests numbers 13 and 19 were only partially consumed. The burning in all cases was bright and clearly photographed. The rates of burning are given in figure 15. The rate, observed from the motion picture film, was determined in three cases as 3.8, 2.56, and 2.35 inches per second, averaging 2.9 inches per second. In each case, the rates varied as the flame passed along the surface, probably reaching peak velocities of 6 inches per second and other rates that were very slow. The brightness indicated that the aluminum was involved in the combustion delivering considerable heat from the 0.05 grams of fuel available. The small amount of smoke produced was no doubt a factor of the high flame temperature. It further showed that zero-gravity did not subdue this flame. Apparently there was little in such a thin material to inhibit the diffusion of oxygen molecules from entering the flame zone. In several cases a flame was noted at the adhesive after the specimen burn was completed. In test number 25 the corrugations reportedly "helped" (crew comment) the fire burn slower. Vacuum venting could have been a factor in test number 13 not burning to completion but the time of venting is not identified. Water spray in test number 19 is also not easily interpreted as the crew reported none was seen at the nozzles.

Nylon - Specimens from tests number 2 and 8 were scheduled for return and analysis. They did not ignite, however, as seen in figures 5, 6, and 7. The igniter did glow each time the control was actuated, which was three or more times. Specimens number 14 and 20 also did not ignite. Test number 26 had a different geometry. As part of the series intended to burn free and drift while burning, it did not have the corner tabs noted in the pictures of specimens 2 and 8. Also, there was less nylon surrounding the igniter wire. Ignition took place on the second try. The entire surface of specimen 26 was soon covered in flame. The fuel did not separate from the igniter--but continued to burn for 10 minutes, 43 seconds during which time it melted and tended to the spherical shape of minimum surface. Boiling of the high viscosity melt was noted and the fire was deliberately quenched by opening the vent. Results were so different from specimens 2 and 8 that this test specimen was also returned for analysis. Figures 12 and 13 show a plan view and a side view of specimen 26. It is significant that self-extinguishment within the experiment time did not occur.

Neoprene-Coated Nylon Fabric - All five specimens of neoprene-coated nylon ignited very quickly but the material did not burn smoothly. As they nylon side became heated it showed considerable shrinkage, causing the material to curl. It tore loose from the frame in an erratic manner giving a series of motions that disturbed the burning severely. Partial self-extinguishment took place as the burning face was covered when rolled up one full turn or more. The venting (test number 15) caused a significant flareup. Rates of surface burning could not be determined. Some self-extinguishment took place as the yellow color of the nylon could be seen when the specimens were removed. The burning mode exhibited "lots of flashing and sparking" to quote the crew observer.

Polyurethane Foam - All five specimens ignited very quickly and burned rapidly along the entire 2 inch surface (the exposed surface not contacted by the igniter was 1 1/2 to 1 3/4 inches long). Venting to extinguish (test number 16) caused a spectacular flareup with two blue spheres of flame at fadeout. This extinguishment was relatively effective as some residue was visible at both supports. Water was unsuccessful in extinguishing due to the reduced water flow. A stream of water was visible in the film but only a few small droplets struck the burning material. The partially supported specimens burned without becoming detached from the single point support. The average burning rate 0.72 inches per second. Fire persisted following the surface burn until all fuel was consumed.

Paper - Another result which was not anticipated was the incomplete burning of the paper. It has been theorized that in the weightlessness environment, two burning modes are possible. One is propagation of a flame along a surface. A second mode of burning is considered non-steady-state as the products of combustion, remaining where they are when released, blanket the fuel and keep the fresh oxygen away from the fuel even though the barrier of gas is believed to be less than 1/2 inches thick. The gaseous products are in motion as they slowly diffuse but this rate is not rapid enough to permit this mode of burning to continue. The extent of the surface burn on paper, however, showed that the depth of burn was probably 0.004 to .006 inches (two surfaces were seen in contact with blue flame and the total paper thickness was 0.009 inches). The condition of the "ash" remaining from test 11 caused Commander Carr to note its scientific value and to bring it back with other specimens (see figure 14). The paper was examined microscopically. The area was estimated to be 1.9 square centimeters. Similar size specimens of the same type of paper were weighed before and after burning in air (one-g). Further work with Differential Thermal Analysis (DTA) was carried out to measure the remaining fuel energy in the ash. Other work was done using lower pressures at one-g to try to simulate the major zero-g effects of flame color, flame height, burning rate, and condition of the ash.

The "diffused pale blue flame as the paper continued to burn" was not noted in any of the film although the television of test number 17 showed this.

Teflon Fabric - In each case the material burned adjacent to the igniter but quickly self-extinguished as the heater wire cooled. As the material did not support combustion in this mode the extinguishment test results are not applicable. The igniter wire was heated a second time in test number 18 but as the fuel in contact with the igniter had burned previously it has no effect. This material burns upwards in one-g in oxygen at this same pressure. Furthermore, in one case where the fuel was a tubular piece of electrical insulation, Teflon continued to burn in the earlier aircraft zero-g tests, perhaps because the wire it surrounded was the Nichrome heater wire which maintained a higher heat level for the eight seconds or so that the weightlessness lasted in that test.

SPECIMEN CONDITION

All specimens appeared to be clean and in good condition before tests. All igniters glowed indicating hardware was electrically functional.

ONE-G WORK

Comparative data is one-g was obtained using identical fuel specimens in a similar work chamber and in various atmospheres. Pre-mixed gases containing oxygen and nitrogen were used to test at 20.8, 64.0, 80.6, and 100 percent oxygen at a variety of pressures. Horizontal, vertical-up, vertical-down, and 45° down test burns were made. Thermocouples were positioned near the specimens in some one-g tests.

The film received from SL-4 was reviewed in detail. Rates of burning and flame height were estimated. The television coverage was also reviewed. A sound film was made with all available photography.

In view of the unique nature of the soft blue diffused flame produced by the paper, a flame not visible on the motion picture but visible on the television, a series of tests were made in one-g to note the minimum pressures at which paper would burn. Finally, a thermogravimetric analysis of the paper used in M-479 was made, together with the specimen of charred paper from test number 11.

DIFFERENTIAL THERMAL ANALYSIS

The ash returned from SL-4, obtained from specimen number 11, was examined in detail.

Weight - The ash from test specimen number 11 weighed 0.0088 grams. Similar sized pieces of the same paper weighed 0.0340 and 0.0323 grams. Therefore, an average weight of 0.0331 grams was used as the estimated weight of the paper that produced the ash returned from SL-4. Three sections were tested by use of the DTA.

D.T.A. Results - The three sections taken from flight specimen number 11 were evaluated with the Differential Thermal Analysis equipment. The atmosphere was oxygen. The flow rate was 1.8 cubic feet per hour. Results are as follows:

Flight Specimen	Weight, Grams	Percent of Spec.	Calories Released	Cal./gm., Measured	Probable Unburned Wt, gm (calculated)
Section 1	0.0004	4.5	0.537	1,343.38	0.0015
" 2	0.0006	6.8	1.19	1,997.52	0.0025
" 3	0.0013	14.8	1.75	1,347.43	0.0049

Uncharred paper was measured for comparison and found to have a heat value of 1,043.37 calories per gram. For this heat value of the paper the calories available in uncharred paper of the same size as the test sections were calculated and, finally, the percentage of fuel available in the charred sections.

Specimen	Percent of Spec.	Calculated Unburn Wt.gm	Calories Available	Calories Remaining	Percent Fuel Rem	Average
Section 1	4.5	0.0015	1.57	0.537	34.2	
" 2	6.8	0.0025	2.62	1.19	45.4	37.9
" 3	14.8	0.0049	5.14	1.75	34.0	

DISCUSSION

Differential Thermal Analysis (DTA) - It is concluded that the paper used in test number 11 had 37.9 percent of the fuel energy remaining as ash. Or, to express it the other way, the paper was 62.1 percent consumed. This value does not represent the whole story, however, as the products of combustion were not examined. In other words when the paper is fully oxidized it produces 1,048.37 calories per gram. In zero-g, however, with a slow burning soft blue flame as was noted, it is assumed that there was insufficient oxygen available to produce that high a heat value. Perhaps the value was only two-thirds to three-fourths as high with many complex organic compounds being produced in the pyrolysis, as well as methane, carbon monoxide and hydrogen, instead of complete combustion producing carbon dioxide and water. In such a case the heat liberated from a fire in quiescent air at zero-gravity can be expected to produce only 41.5 to 46.5 percent of the "available" thermal energy from completely exposed thin specimens, such as a piece of paper. Carrying this train of through one step further it should be expected that after a fire in zero-gravity the toxicity and flammability of the gaseous products produced would be significantly greater than a similar one-g fire.

Rates of Burning - Rates of burning in zero-gravity were calculated from the film produced at 24 frames per second. For the aluminized Mylar three rates were observed. They were close enough to use the actual average of 2.9 inches per second, figure 15, with a maximum deviation of 0.9 inches per second or 31.0 percent above the average. As noted earlier this material did not burn uniformly. The polyurethane foam was measured in four different tests with an average of 0.72 inches per second with a maximum deviation of 0.22 inches per second, or 30.6% below the average. No value would be given the paper in zero gravity as the flame was invisible just after ignition except for the short interval when noted on the television screen. At that instant the extent of burning could not be determined, nor was it possible to note the amount of paper unburned when the fire went out by venting of the atmosphere. The rate of burning for the nylon was estimated as being below 0.01 inches per second. Only one specimen ignited and there was no certainty when the flame reached the opposite edge as the illumination of the flame was so low. The neoprene coated nylon moved too much to give a burning rate except to estimate it as being less than 0.5 inches per second.

Flame Heights - Flame heights involved considerable estimating as the only dimensional references were the visible fuel holders or unburned specimens. The domed shape of the flame, as perturbed by the gases released at the surface, caused variations. Only flames perpendicular to the camera line-of-sight are suitable for measurement. For specimens observed by a line of sight perpendicular to the fuel surface this became an impossibility.

Gap Propagation - In all cases tested (with paper) the flame crossed the gap (1/8", 1/4", and 1/2"), although illumination was insufficient to give strong confidence to this conclusion. Likewise simultaneous ignition of both specimens, or face ignition, possibly contributed to increased rates of burning over a single sheet of paper. Results are too limited here for a positive conclusion.

Smoke - Visible smoke patterns noted after the fires went out and while the air was still unaffected by convection were noted in a few cases. The most noticeable pattern was from two 35 mm. still photographs taken during the burning of polyurethane foam (Figures 17 and 18). The burning polyurethane foam, test number 10, (figure 17) shows variations in the circular flame corona that match the smoke patterns several (?) seconds later (figure 18). The time delay between the photographs is not recorded.

ONE-G TESTING

One-g control data was obtained by identical fuel specimens in a similar test chamber in various orientations. The test atmospheres included 20.8, 64, 80.6 and 100 percent oxygen at a variety of pressure. Burning was horizontal, vertical-up, vertical-down, and 45^{o}-down. Results were documented by 16 mm motion picture (DAC).

Rates of Burning - Figure 15 gives the rates of burning observed for one-g in the orientation tested. Results in figure 15 are from the same atmosphere as provided in Skylab.

Flame Height - While the flame dimension was not an objective of any significance in the Skylab tests, it was a factor in the flash-over to adjacent materials, tests 31 through 37, although that was limited to paper only. Estimates are given in Figure 16 for 65% oxygen at 5.2 psia.

Blue Flame Replication - The diffused pale blue flame characteristic of zero-g burning of paper was duplicated in one-g by using a minimum amount of oxygen. For 64 percent oxygen the lowest total pressure at which a flame would continue to spread along the surface of paper was 50 mm Hg. For 80.6 percent oxygen the value was 32 mm Hg. Air, 20.8 percent oxygen, gave a minimum pressure of 300 mm Hg. These values Figure 19, are plotted in Figure 20. Most of the tests were upward burning but horizontal burning or downward burning gave substantially the same results. Pressure rises during combustion at the low pressures were more significant than at the higher pressures. In very case, that it was noted, the peak pressure was higher during the test than at the start. The burning rates at these marginal conditions were very low.

The curve in Figure 20 suggests conditions for evaluating photography in future zero-g flammability, and to an extent, five detections. In addition, it provides data points for flammability testing in one-g, applicable to zero-g, for paper. The extent to which it is applicable is not clear. Burning rates, self-extinguishment, and products of combustion may prove to be correctly demonstrated in one-g at these pressures. But there is insufficient data at this time to appraise this as a one-g technique for simulating all aspects of a zero-g fire.

FILM RESULTS

A 16 mm sound motion picture film of the zero-g results was performed and is available from the Lyndon B. Johnson Space Center Film Library. The film is identified as "Skylab Zero-G Flammability Studies, JSC 74-652."

CONCLUSIONS

Thirty-seven tests were performed in Skylab Experiment M-479. The tests took 6 hours, 18 minutes meeting all the objectives of the experiment. The following is concluded.

1. Ignition was not quantitatively evaluated in zero-gravity but it appears to be identical in heat and time as in one-g considering the variety of materials and number of tests conducted.

2. Burning rates are, in general, much slower in zero-gravity than they are for the same materials and atmosphere in one-g. From the standpoint of upward or horizontal burning the zero-gravity rates are considerably slower, in that there is no tendency for rates to increase exponentially as on Earth where, during the initial phase, the longer the material burns the larger and hotter the flame becomes. From the standpoint of downward burning in one-g there are also differences. Very thin material such as Mylar film burns at approximately the same rate as in one-g where orientation is not a significant factor (for this material). Thicker material such as 9 mil paper burns slower in zero-gravity as the flame spreads in 2 modes. One is along the surface. This is uniform and depends on the temperature and composition of the material. In zero-g this mode predominates and is characterized by a soft blue diffused flame (for paper) that is dimensionally small, reportedly extending one-half to three-quarters of an inch. It proceeds along a surface at a "slow" rate (probably 0.1 inch per second), but was invisible on film returned from M-479. The other mode, inward, is apparently dependent on a diffusion process. This is restrictive and in many cases, not possible as explained earlier.

3. Extinguishment by vacuum is effective in that the fire will go out as the available oxygen decreases to some level such as 6 millimeters of oxygen. A significant side effect that deserves consideration is the intensification that develops during the initial phase. The flame can be extremely soft and small with a nearly negligible burning rate and, as the air flow produces a forced convection, it will greatly intensify. If such a procedure was used in a large volume and the time to reach a cutoff pressure was significantly long the fire could do considerable damage before going out.

4. Self-extinguishment of an undisturbed fire was not noted. It appears unlikely if the physical properties of the unburned material sets up mechanical activity as in the shrinkage of a polymer or the boiling of a high viscosity melt. It does occur in the case of Teflon fabric in 62% oxygen at 5.2 psia or less. It also occurs in the case of paper. As a conclusion, it can only be said that self-extinguishment is possible but all criteria are undefined.

5. Extinguishment by water is possible provided the application is controlled and adequate. If insufficient water strikes a burning material it always causes a momentary disturbance exhibited by a flareup which can scatter burning material and also permit a flashover by the resulting larger flame.

6. Flashover to adjacent material is possible in zero-gravity. In the case of paper the flame will cross a gap of one-half inch. The absolute upper limit is undefined as yet. The flame visibility problem discussed earlier makes interpretation difficult.

7. The performance of flammability tests by a trained operator in zero-gravity is very feasible by using hardware of the type provided by the M-512 facility. Photographic coverage is, of course, quite important. The only conclusion to make in this regard is that an f-stop of 2.8 is not adequate for a shutter speed of 1/60 with an 18 mm lens and color infrared film #3443, color SO-168, or color SO-368 emulsion except for the bright flames. The soft blue flame requires a slower shuttle or larger aperture. For the film and equipment listed above, an f-stop of 2.0 made the flame sufficiently visible, however, for the replication tests carried out in one-g.

8. There appears to be no tendency for fuel to become detached and drift as it burns in zero-g. Whatever unbalanced forces exist in the gas evolution of combustion are less than the adhesion or mechanical strength of the ash. For materials that melt, the cohesive forces draw the unburned material into the fire zone.

9. Large convective forces produced in one-g fires are not characterized in zero-g fires.

10. The visibility of a flame is significantly reduced in zero-g. A luminous fire is noted, however, if metals are involved or if conditions are such to produce high burning rates.

11. Fuel with a large temperature spread between the melting point and boiling point burn with an agitated pulsating flame that can continue for a substantially long period of time.

REFERENCES

1. Kimzey, J. H., "Flammability in Zero-Gravity," 55th National Meeting, American Institute of Chemical Engineers, February 7-11, 1965, Houston, Texas.

2. Kimzey, J. H., "Flammability During Weightlessness," NASA TXM 58001, May 1966.

3. Kimzey, J. H., et al, "Flammability in Zero-Gravity Environment," NASA TR R-246, October 1966.

4. Kimzey, J. H., "Zero-Gravity Flammability," In ME69-1, George C. Marshall Space Flight Center Meeting, "Space Processing and Manufacturing," October 21-22, 1969, Huntsville, Alabama.

5. Experiment Implementation Plan for Manned Space Flight Experiments, "Zero-Gravity Flammability," Experiment No. M-479, October 10, 1967, Lyndon B. Johnson Space Center, Houston, Texas.

6. Experiment Requirements Document for Zero-Gravity Flammability (Experiment M-479) of January 20, 1974. Repository No. SE-010-003-24, CCBD No. 800-70-0054, George C. Marshall Space Flight Center, Huntsville, Alabama.

7. Mission Requirements Document, "Third Skylab Mission," SL-4 of August 27, 1973. I-MRD-001F, Volume III, Published Jointly by JSC, Houston, Texas and MSFC, Huntsville, Alabama.

FIGURES

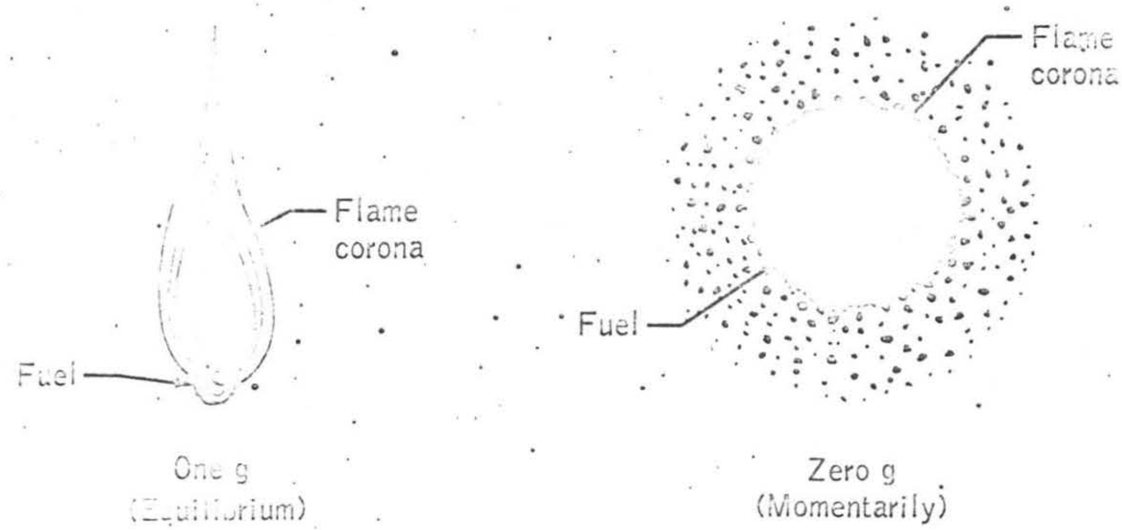


Figure 1.- Comparison of fuel burning at one-g and zero-g in oxygen atmosphere.

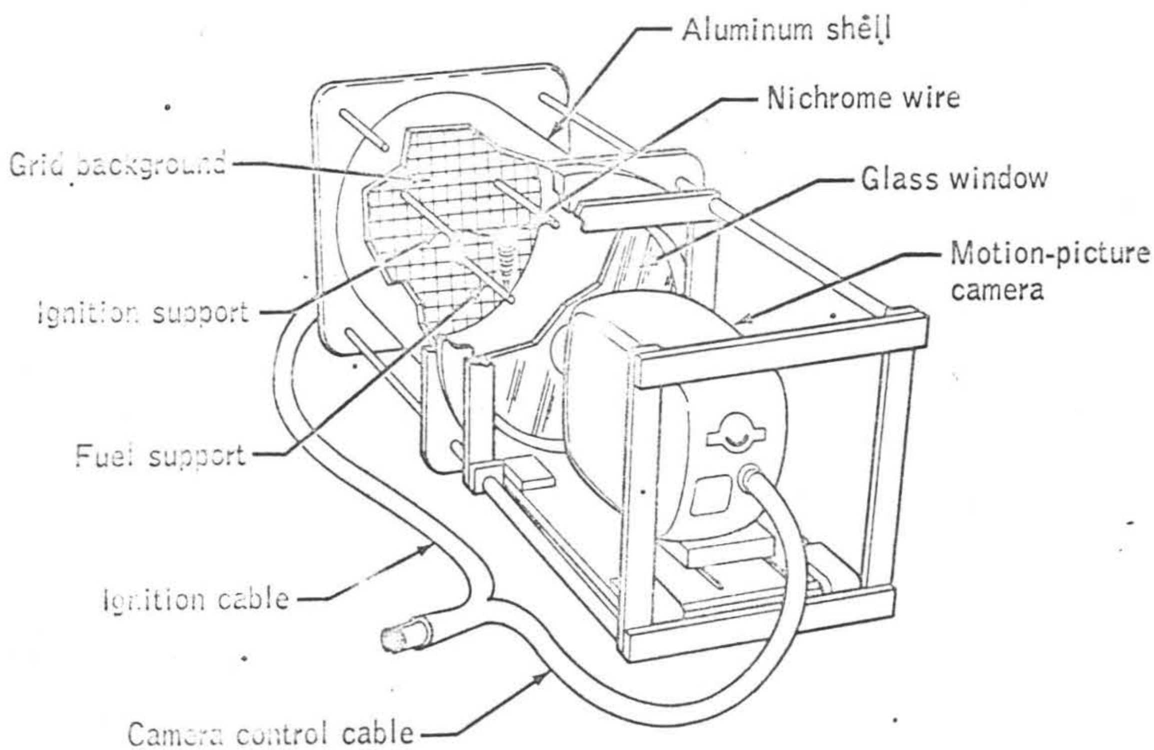


Figure 2.- Zero-g flammability chamber.

STRUCTURES AND MECHANICS DIVISION
JOHNSON SPACE CENTER
HOUSTON, TEXAS

ES5-74-136-07

SUBJECT/TITLE: AIRCRAFT FLAMMABILITY TEST

Figure 3

MATERIALS

DACRON THREAD

NEOPRENE RUBBER, FOAMED

NEOPRENE RUBBER TUBING

PARAFFIN

POLYURETHANE RUBBER

SILICONE RUBBER

STYRENE PLASTIC

TEFLON TUBING

NASA-S-72-2104-V

SKYLAB EXPERIMENT M-479 ZERO GRAVITY FLAMMABILITY

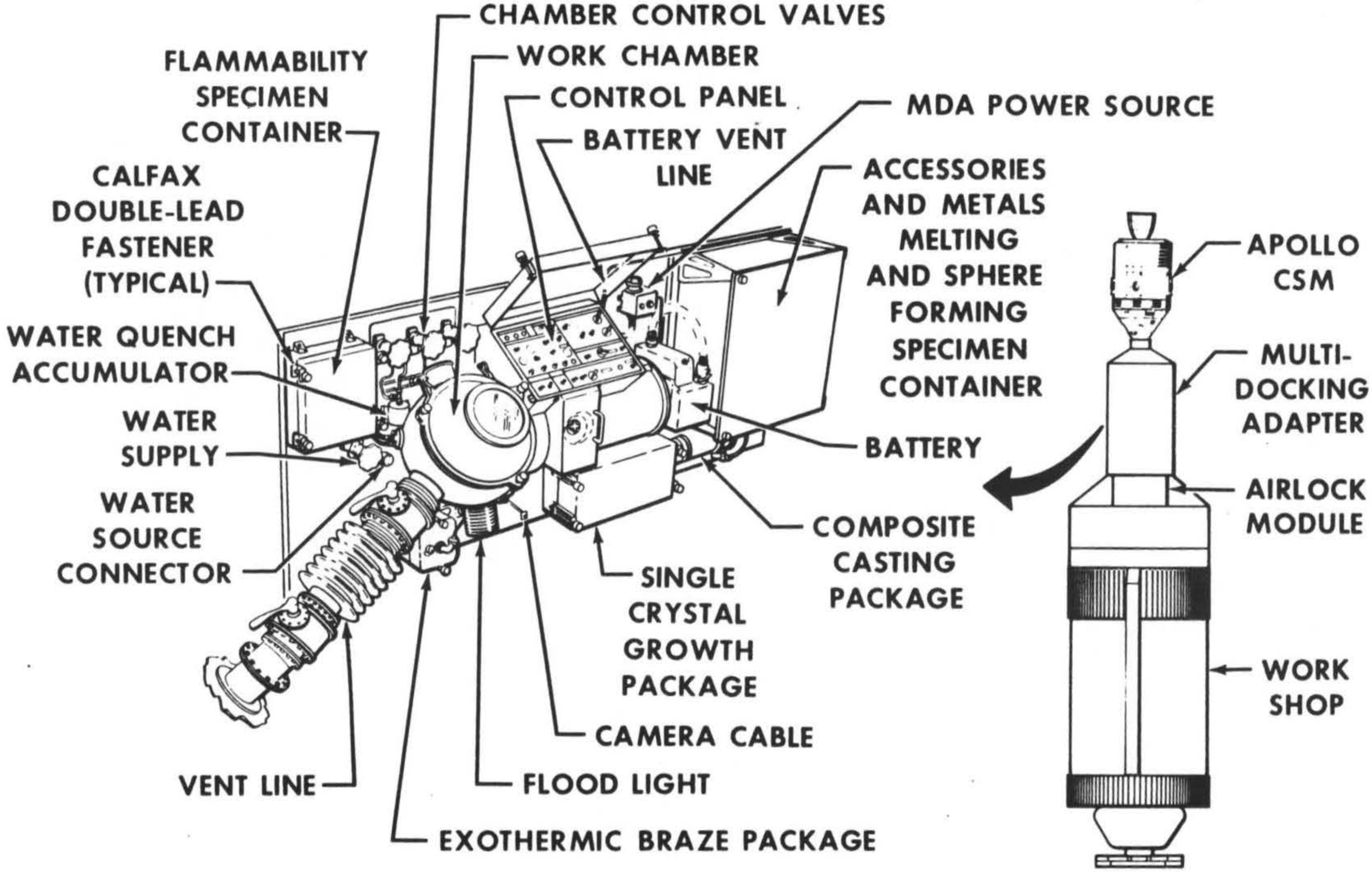


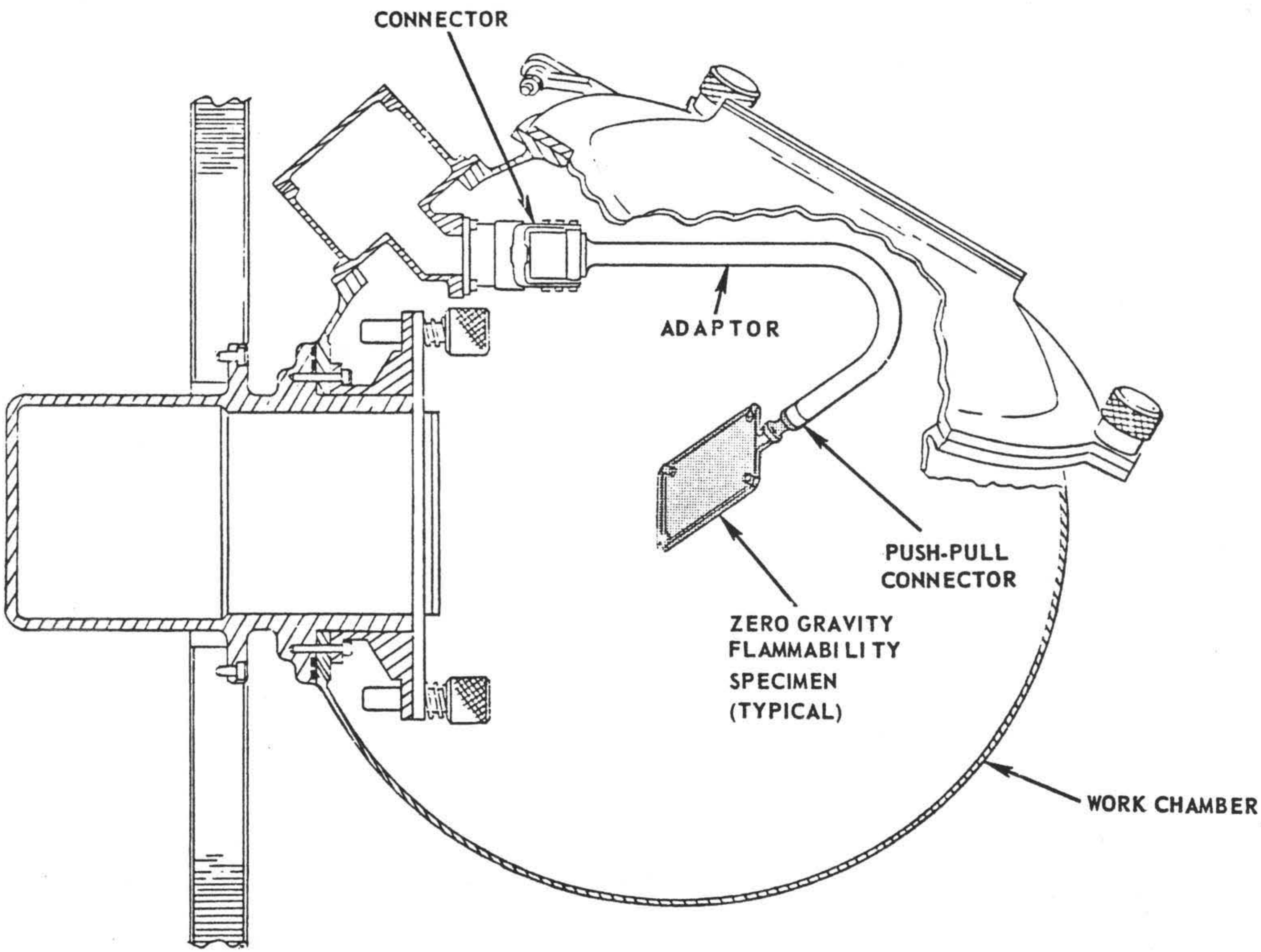
FIGURE 6

TEST	START	END	ELAPSED
1-9	035-13-39-50	16-01-54	2-22
10	035-19-21-46	19-27-38	-06
11-12	035-19-42-12	19-55-56	-14
13-15	035-20-21-46	20-38---	-16
16-18	035-20-50-24	21-28-52	-38
19-30	036-00-54-38	03-08-22	2-14
31-37	037-02-58-54	03-26-23	-28

Total 6 Hr/8min

Figure 8

Voice Recorder Times



INSTALLATION OF ZERO GRAVITY FLAMMABILITY ASSEMBLY

FIGURE 7

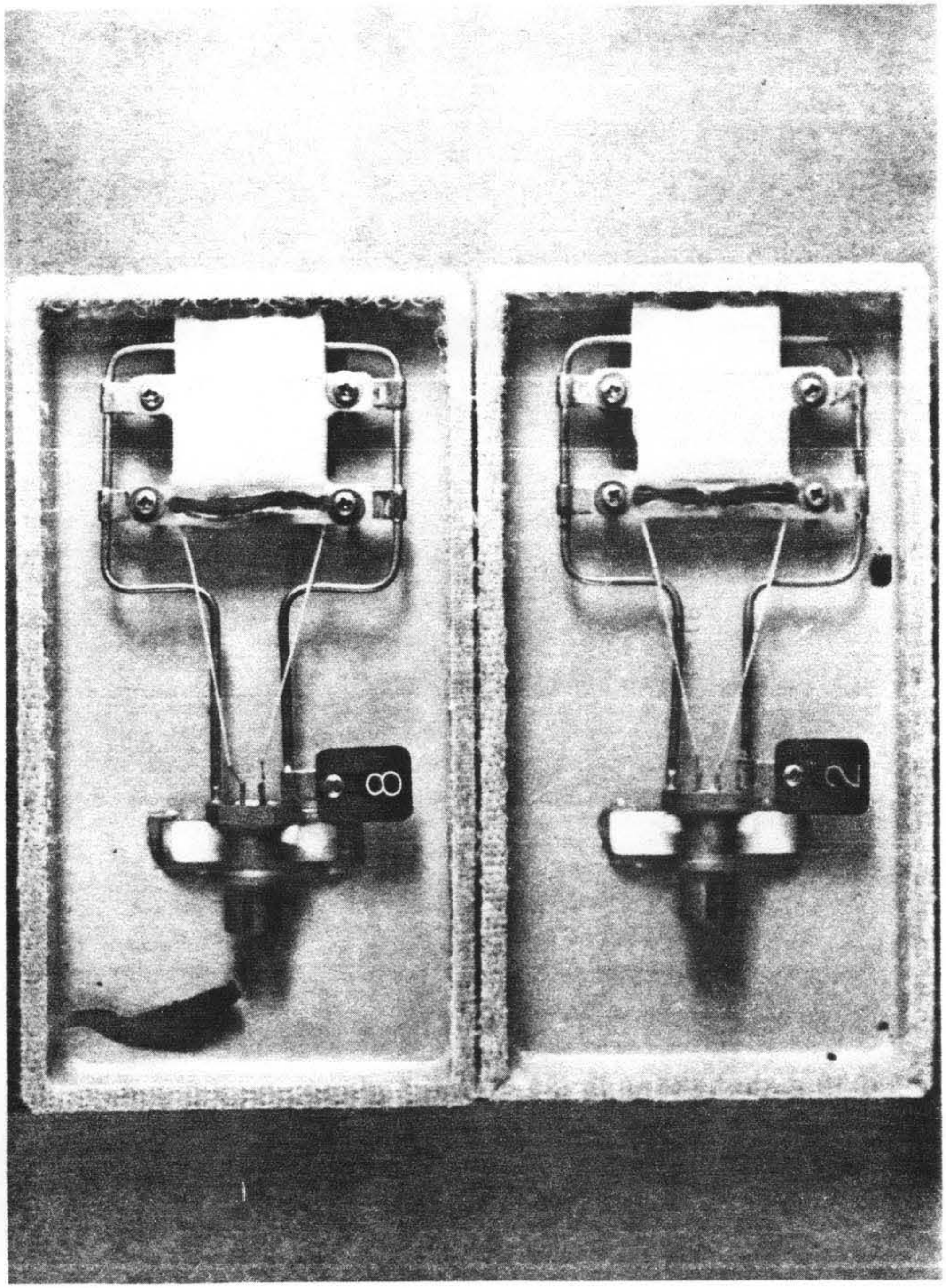


Figure 9 - Specimens 2 and 8 as received

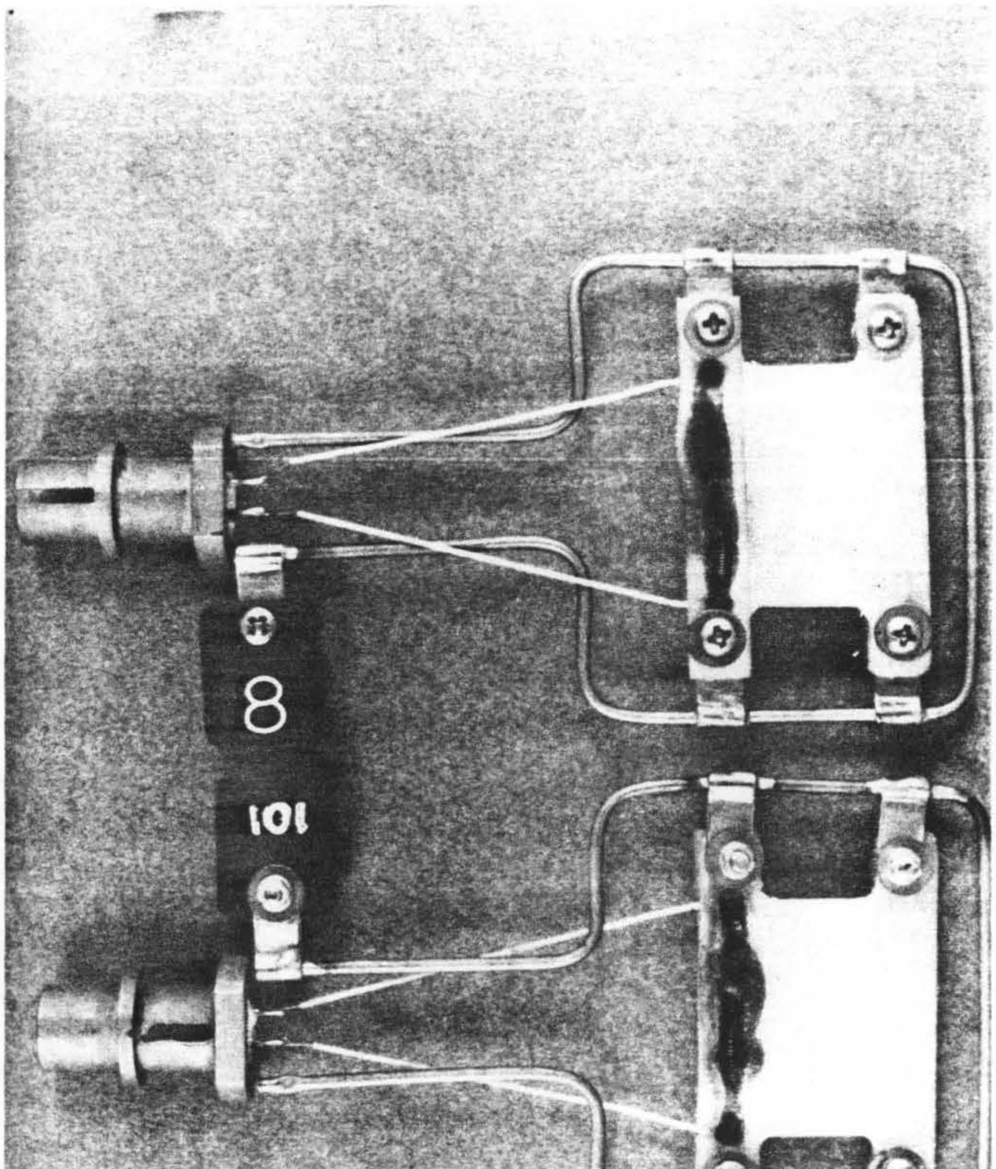


Figure 10 - Specimens 2 and 8

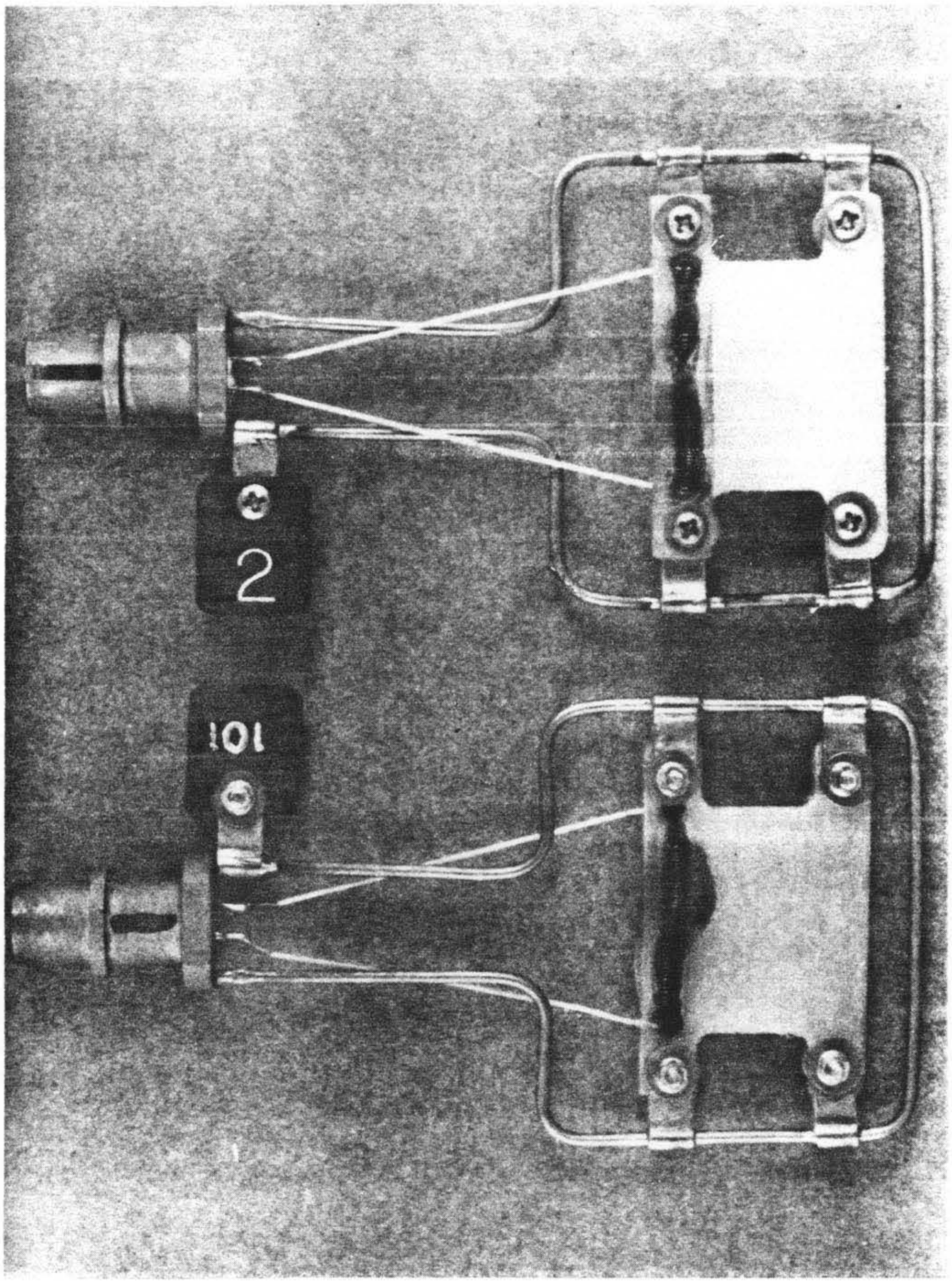


Figure 11- Specimens 2 and 8, opposite view

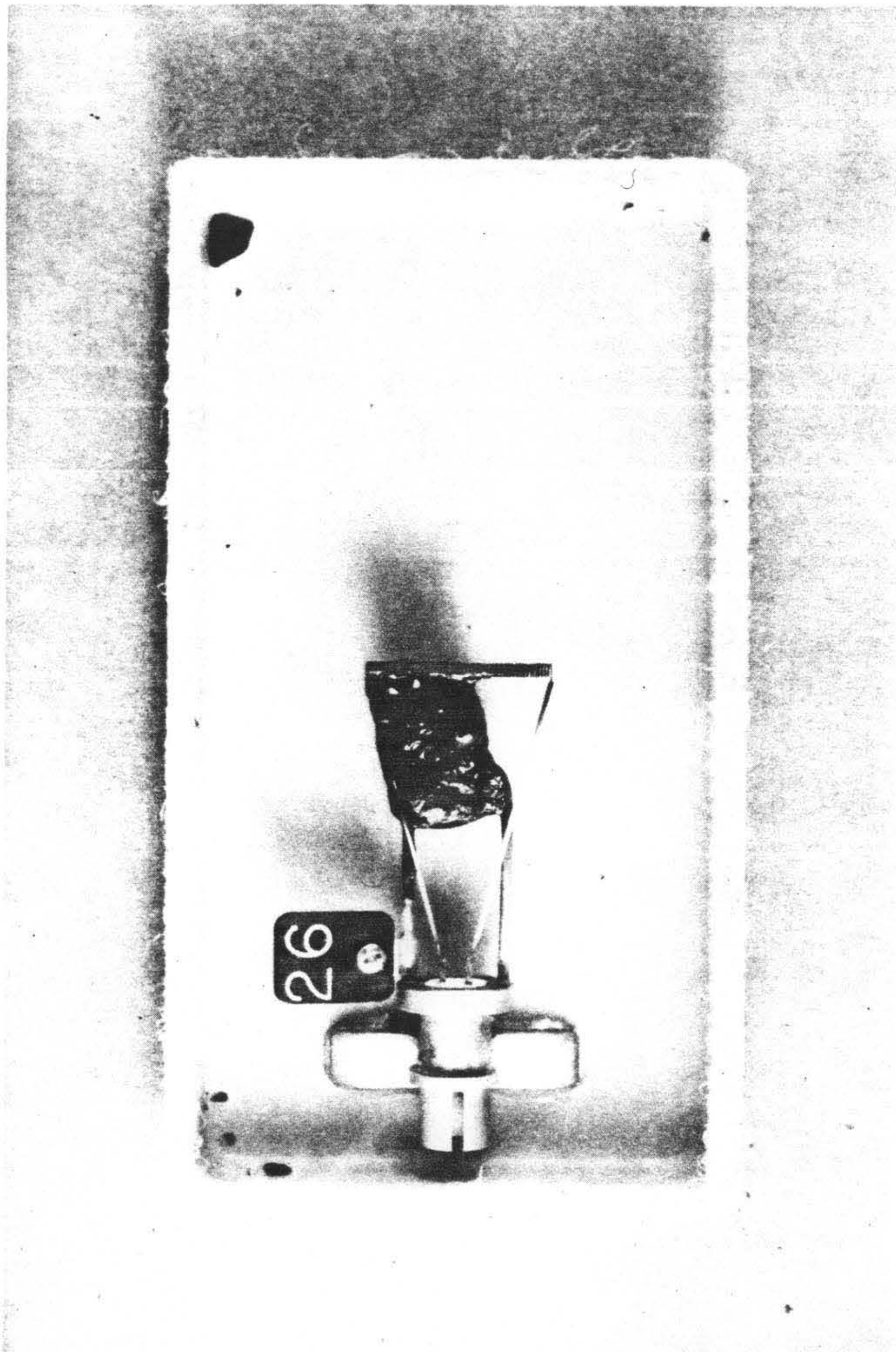


Figure 12 - Specimen 26

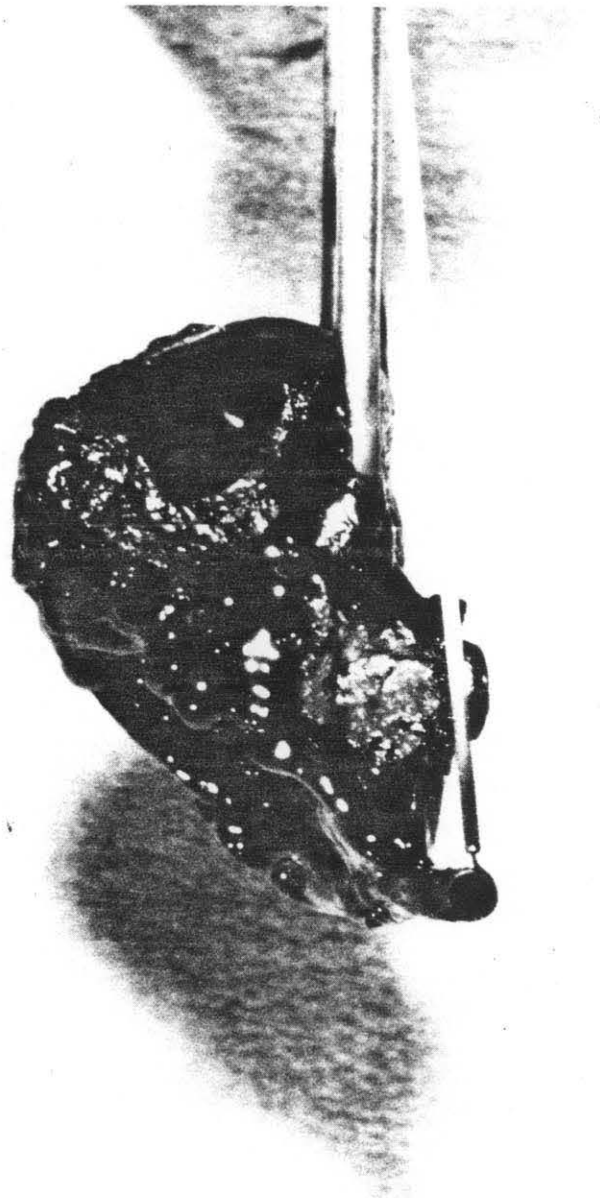


Figure13, Specimen 26, side view

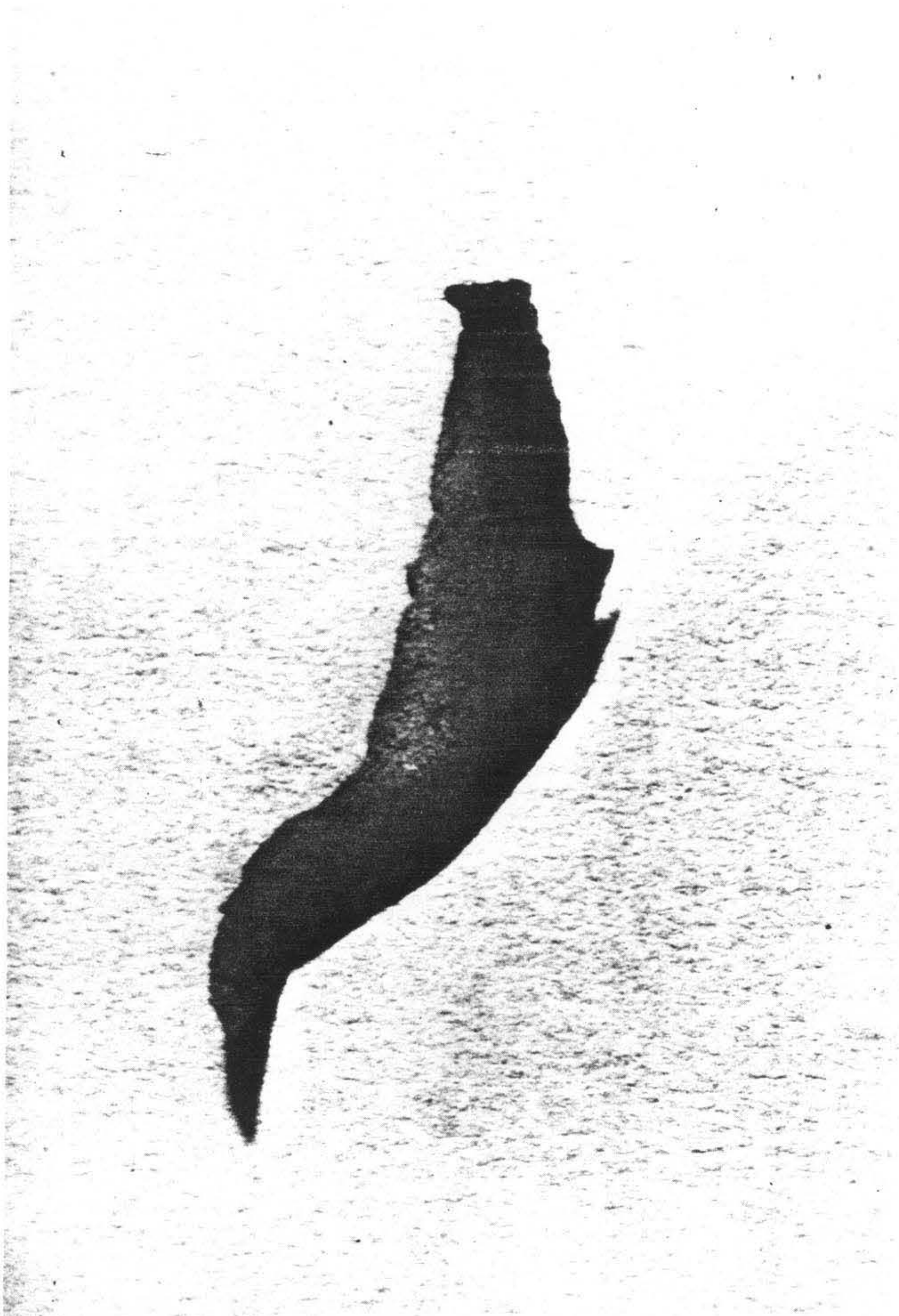


Figure 14 - Specimen 11 remnant

U.S. GOVERNMENT PRINTING OFFICE 1986 659-014/40021

RATES OF BURNING

(ATMOSPHERE = 65% O2 AT 5.2 PSIA)

FUEL[1]	ORIENTATION	ONE-G, IN/SEC(CM/SEC)	ZERO-G IN/SEC(CM/SEC)
ALUMINIZED MYLAR	DOWN	4.8 (12.2)	2.9[2] (7.3)
	DOWN, 45°	<0.1 (0.25)	
NYLON	HORIZONTAL	0.03 (0.076)	<0.01 (0.025)
NEOPRENE COATED NYLON FABRIC	UP	0.81 (2.06)	<0.5 (1.2)
POLYURETHANE FOAM	DOWN, 45°	4.8 (12.2)	0.72[3] (1.83)
" "	UP	5.6 (14.2)	
PAPER[4]	DOWN	0.27 (0.68)	UNDETERMINED
"	HORIZONTAL	0.35 (0.88)	
"	UP	0.46 (1.17)	
TEFLON FABRIC[5]		0.0	0.0

1. IDENTICAL FUEL SPECIMENS USED IN BOTH ONE-G AND ZERO-G.
2. AVERAGE OF THREE OBSERVED RATES: 2.35, 2.56, AND 3.8 INCHES PER SECOND.
3. AVERAGE OF FOUR OBSERVED RATES: 0.8, 0.8, 0.51 AND 0.78 INCHES PER SECOND.
4. BURNING RATES FOR PAPER AT MINIMUM OXYGEN, FIGURE 19, ARE MUCH LOWER.
5. FABRIC WOULD NOT SUSTAIN BURNING IN TEST ATMOSPHERE

FIGURE 15

FLAME HEIGHT

(ATMOSPHERE = 65% O_2 AT 5.2 PSIA)

FUEL[1]	ORIENTATION	ONE-G, in. (cm)	ZERO-G, in. (cm)
ALUMINIZED MYLAR	DOWN	0.125 - 0.5 (.2-1.2)	.25 - .5 (.6-1.2)
NYLON	HORIZONTAL	1.5 - 2.0 (3.7-5.0)	.25 (0.6) INITIAL
	DOWN 45°	0.25 - 0.5 (.6-1.2)	1.0-1.5(2.5-3.7) FINAL[2]
NEOPRENE NYLON FABRIC	UP	0.5 (1.2)	0.125 - 0.25 (0.3-0.6)
POLYURETHANE FOAM	DOWN 45°	0.75 - 1.0 (1.8-2.5)	1.25 (3.1)
PAPER[3]	HORIZONTAL	1.0 - 1.5 (2.5-3.7)	0.5 - 0.625 (1.2-1.6)
	DOWN	0.75 - 1.0 (1.8-2.5)	
TEFLON[4]		0.25 (0.6)	0.25 (0.6)

NOTE:

1. IDENTICAL FUEL SPECIMENS USED IN BOTH ONE-G AND ZERO-G.
2. FLAME HEIGHT INCREASED AS PLASTIC MELTED AND BOILED.
3. FLAME HEIGHT AT MINIMUM OXYGEN IS MUCH LOWER IN ONE-G (FIGURE 17); 0.125 - 0.250 INCH (0.3 - 0.6 CM).
4. FLAME NOTED ONLY WHILE IGNITER WIRE WAS LUMINOUS.

FIGURE 16

FIGURE 9. SKYLAB IN-FLIGHT TESTING

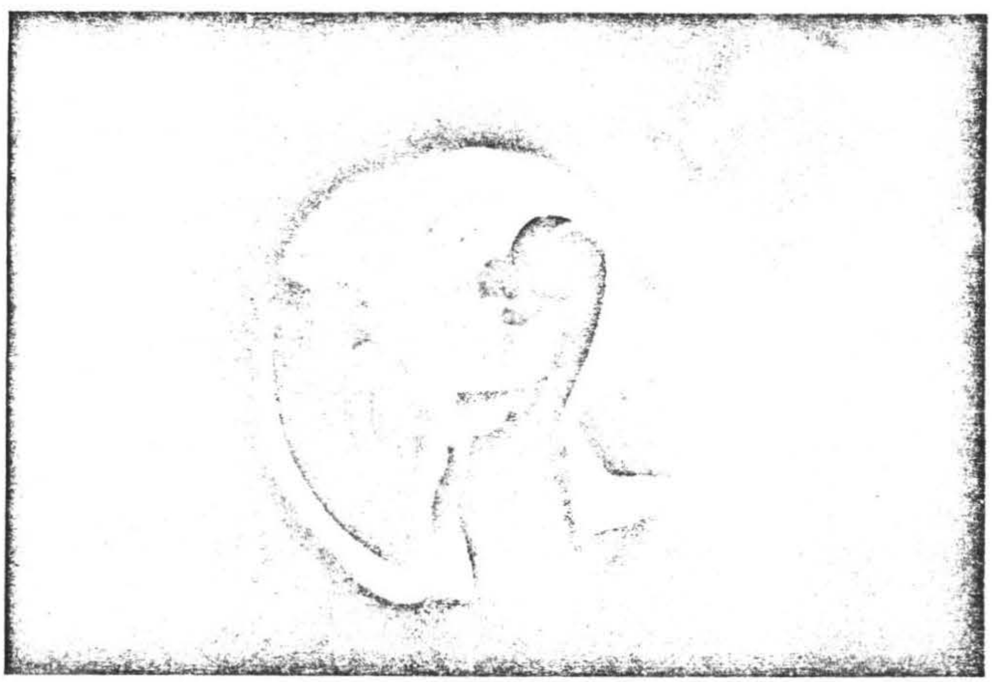


FIGURE 10. PHOTOGRAPH OF BURNING POLYURETHANE FOAM IN TEST NUMBER 10

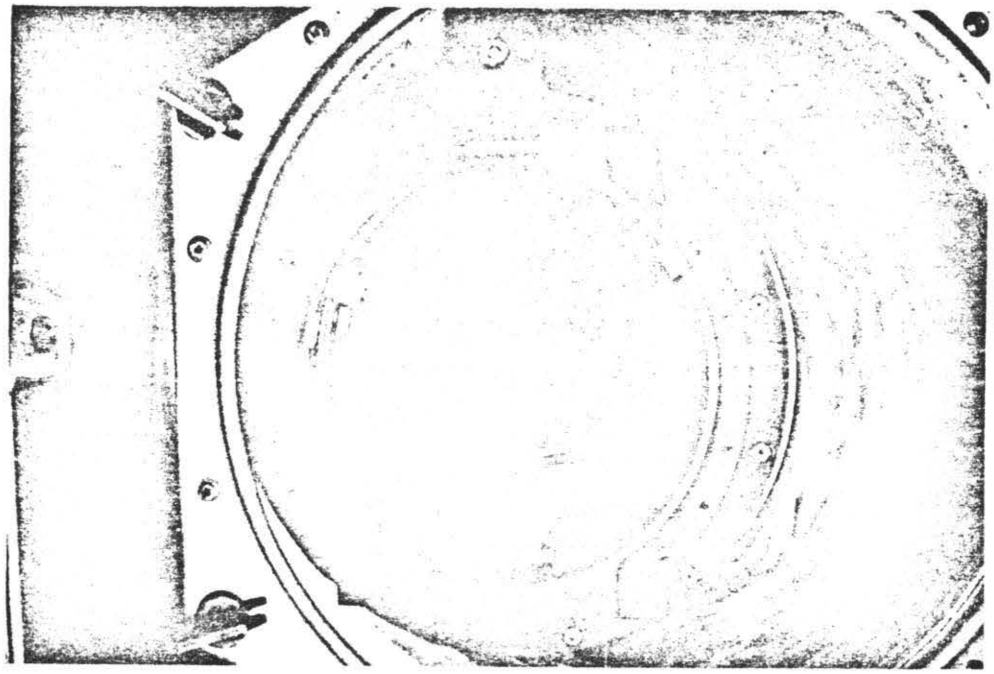


FIGURE 18. PHOTOGRAPH OF SMOKE PATTERN OF BURNING POLYURETHANE FOAM IMMEDIATELY AFTER FIRE WENT OUT

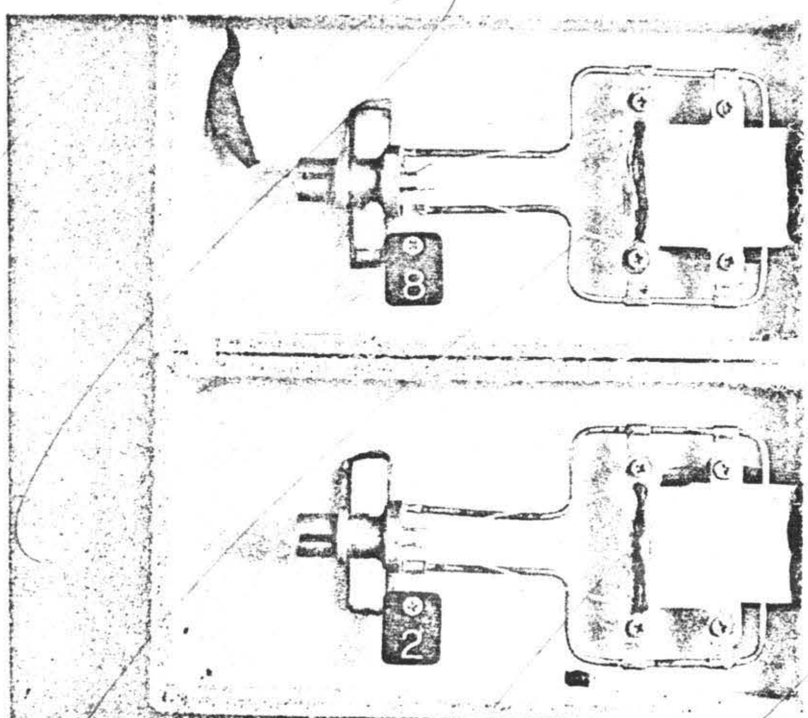


FIGURE 12. PHOTOGRAPH OF SPECIMEN RETURNED FROM TEST NUMBER 2 WHICH DID NOT IGNITE

COMBUSTION OF PAPER IN ONE-G TO
DETERMINE MINIMUM OXYGEN TO
SUSTAIN A FLAME

TEST	ORIENTATION	HT.	RATE	PERCENT O_2 IN N_2	COLOR	PRESSURE, IN IN. HG INITIAL	MAXIMUM
62	UP -45^{o}	.1875 TO		20.8	BLUE	380	--
63	UP	.25		64	ORANG.-YELL.	125	--
64	HORIZ.	1"		64	SOFT BLU-PURP.	65	--
65	"			64	" "	52	80
66	"	1/2-1"		64	" "	60	--
68*	DOWN (EXT. @50%)			20.8	" "	300	310
69*	DOWN R =	1/8"-1/4"	VERY LOW .207in./sec	64	DEEP BLUE	60	80
70*	DOWN	"	.255	64	"	53	68
71*	UP	"	.788	64	"	50	70
72+	HORIZ.		.310	64	"	50	--
75+	DOWN		.290	80.6	SOFT BLUE	35	--
78+	DOWN		NOT MEASURABLE	80.6	"	32	44
80	UP			80.6		32	46
82	HORIZ.			80.6	LG. YELL. EDGE	75	110
83	HORIZ.			80.6	SM. BLUE	32	48
89	HORIZ.			100		28	48
90	HORIZ.			100		28	50
92	DOWN (CAMERA OFF MID)			100		28	52
93	UP		7"-8"	100	YELL. EDGE	30	51

*FILM: (10,105 T-3072)

+FILM: (10,290 T-3095)

FIGURE 19

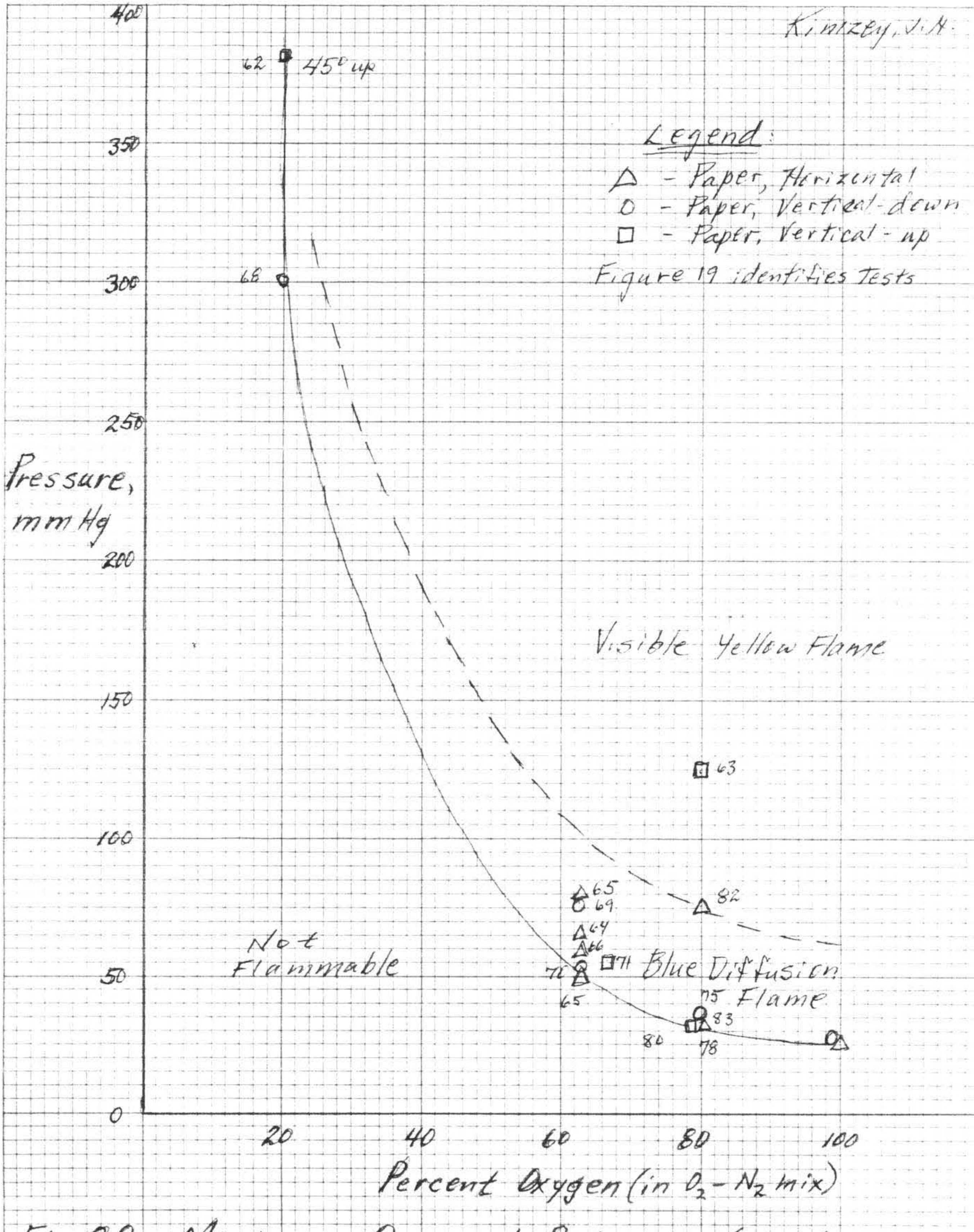


Fig. 20. Minimum Oxygen to Produce Sustained Burning of Paper, One-G