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THE EFFECT OF ATMOSPHERE SELECTION AND GRAVITY ON BURNING RATE AND IGNITION TEMPERATURE

OCTOBER 1968

Prepared Under Contract No. NASw-1539

by

Advance Biotechnology and Power Department
McDonnell Douglas Astronautics Company – Western Division
Santa Monica, California

for

Biotechnology and Human Research Division
Office of Advanced Research and Technology
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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FOREWORD

New engineering data were obtained on burning properties in different representative space cabin atmospheres. Several hundred tests using a standardized cotton cloth specimen were completed for a spectrum of atmospheric compositions at gravity levels representative of spaceflight, launch, and entry conditions. Other pertinent fire prevention data are presented herein and in NASA CR-891, entitled "Engineering Criteria for Spacecraft Cabin Atmosphere Selection."

The work described in this report was conducted for Walton L. Jones, M. D., Director of Biotechnology and Human Research Division, and J. N. Pecoraro, under the direction of A. L. Ingelfinger of the Office of Advanced Research and Technology, Headquarters, the National Aeronautics and Space Administration, Washington, D. C. Acknowledgement is given to Dr. D. Fedderson of NASA MSC for valuable assistance in obtaining the KC-135 zero-g test aircraft and to Donald Griggs, Zero-g Test Director, and Lt. Jack Thompson of the Aeronautical Systems Division, Wright-Patterson Air Force Base, for their valuable assistance in completing the null-gravity testing in the KC-135 aircraft. The work was performed by the Advance Biotechnology and Power Department of the McDonnell Douglas Astronautics Company — Western Division, Santa Monica, California, under NASA Contract No. NASw-1539. Those who contributed to this report are as follows:

R. A. Neustein, Principal Investigator

P. P. Mader, Ph. D.

G. V. Colombo

D. E. Richardson

ABSTRACT

The comparison of atmospheres for fire prevention given in NASA CR-891 reported the initial work completed for this project (ref. 1). Baseline test specimens were selected and new test data presented in the reference, which helped to evaluate the relative effect of atmosphere composition on burning rate and ignition phenomena. The effort was continued and tests were completed that permit a better understanding of the effects of null gravity, elevated gravity (up to 5 g's), and ventilation rate on atmosphere selection from a fire prevention standpoint. An analytical correlation was completed and an equation presented for extrapolating test data from one gravity level to another for the cotton cloth specimen tested. A KC-135 aircraft was used to obtain the null-gravity data and a 10-ft radius centrifuge was used to obtain controlled elevated-gravity data. The spectrum of gravity levels evaluated are considered representative of those that could be encountered during vehicle ground checkout, launch, entry, and spaceflight. Additionally, new data were obtained to permit (1) the comparison of neon diluent from a fire prevention aspect to helium and nitrogen, (2) the evaluation of the pre-ignition and post-ignition decomposition products of the test specimen for application to fire detection, and (3) the evaluation of the potential of inert gaseous nitrogen and helium for their individual fire extinguishing capability.

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INTRODUCTION

A vehicle designer normally selects the cabin atmospheric composition and pressure level based on either one or a combination of design requirements that involve human physiology, low-weight penalty, fire prevention, cost, hardware availability, and compatibility requirements imposed by other vehicle systems. NASA CR 891 (ref 1), presents analysis and new test data that can be used to evaluate some of the engineering trade-offs required in atmosphere selection. The subjects included in the above NASA report are

(1) Comfort zone

(2) Leakage

(3) Airlock system

(4) Atmospheric supply

(5) The effect of atmosphere selection on component heat and mass transfer as well as life support system penalty

(6) Fire prevention.

New fire prevention test data were required and obtained to augment that previously reported. It was not the principal purpose of this study to evaluate materials but to fill in gaps where information was required to help determine the relative effects of atmosphere composition, pressure level, ventilation rate, and gravity level on flame propagation rate and ignition phenomena. Additionally, material decomposition products were analyzed for possible fire detector application, and nitrogen and helium were each evaluated for fire put-out capability. Results of tests and supporting data are presented in the sections entitled the following:

(1) Summary

(2) Test Procedures

(3) Effects of Atmosphere Composition and Gravity Level on Ignition

(4) Effects of Atmosphere Composition and Gravity on Burning Rate

(5) Conclusions.

Section 1

SUMMARY

Preliminary studies of flame propagation in various typical spacecraft atmospheres were performed under Contract NASw-1371 and reported in ref. 1. These studies were performed on standardized test specimens consisting of cotton cloth strips, insulated wires, and wire bundles. Data included flame propagation rates, ignition temperatures, and ignition times under standardized conditions. Various atmospheric compositions that were tested included pure oxygen, oxygen-helium, and oxygen-nitrogen. Most of the data were taken at 1g but some preliminary 5- to 8-sec null-gravity tests were performed in an Aero Commander type aircraft.

During the reported tests, additional data on flame propagation were obtained to provide a better understanding of the problem. Tests were continued using cotton cloth strips, insulated wires, and wire bundles that were used previously. In addition to helium and nitrogen as diluents, neon-oxygen atmospheres were tested. Data were obtained in null gravity for 15 to 20 sec in a KC-135 aircraft and at accelerations of 3g and 5g on a centrifuge. Comparisons were also made between free and forced convection. In addition to tests on flame propagation, chemical analyses were conducted to determine the decomposition products produced by combustion of the cotton cloth strips, and a method was devised for extinguishing fires in an oxygen atmosphere with gaseous helium or nitrogen.

The results of these testing programs may be summarized as follows:

(1) The ignition temperature is essentially independent of the amount and nature of atmosphere diluent but is dependent on oxygen partial pressure and material type. For example, the ignition temperature was lowered from 630°C at 3.5-psia oxygen partial pressure to 550°C at 5-psia pure oxygen for a cotton cloth specimen. Tests indicated that minimum ignition temperature was affected very little by gravity and forced ventilation. For cotton cloth, the ignition temperature was 650°C ± 20°C for all total pressures from 5 psia to 14.7 psia with a 3.5-psia oxygen partial pressure in both the nitrogen-oxygen and helium-oxygen mixtures. From a fire prevention standpoint it would be advisable to increase ignition temperature by lowering the oxygen partial pressure to a minimum.

(2) Ignition energy requirements were greater in atmospheres with increasing helium partial pressures and constant oxygen partial pressures, but were not materially changed in nitrogen-oxygen mixtures

when nitrogen partial pressures were varied. This correlates with the varying thermal conductivity of the mixture and indicates increasing thermal losses from the igniter as the helium concentration increases.

(3) The addition of 1.5-psia nitrogen to 3.5-psia pure oxygen had only a minor effect in reducing the spread of fire. Not until the partial pressure of nitrogen was increased to 3.5 psia did a sizable reduction in the burning rate occur. This agrees with the tests by Klein (ref. 2) which also indicated that the first addition of a diluent had only a minor effect on the reaction rate as compared with the burning rate in pure oxygen.

(4) In null gravity, the burning rate was close to zero for most of the atmospheres tested. Self-extinguishment did occur in one test with normal air as an atmosphere. Typical null-gravity burning rates are presented in Table I below.

(5) Burning rates in zero g are very low because oxygen is supplied to the flame only by diffusion. Tests indicated that a fire in normal air extinguished itself in null gravity when no forced convection was present. Char propagation for the cotton cloth was also very slow in null gravity when no convection was present. Gases resulting from the fire collected around the char front and formed a spherical flame. The fire decreased in intensity and, in one test, extinguished. Extraneous

Table I

BURNING RATES OF COTTON CLOTH STRIPS AT NULL GRAVITY

Total Pressure	Composition	Burning Rate, in./sec
3.5 psia	100% O_2	0.039
5.0 psia	100% O_2	Not measured because burning was not in straight line
	70% O_2, 30% He	0.081
	70% O_2, 30% N_2	0.043
7.0	50% O_2, 50% He	0.052
	50% O_2, 50% N_2	0.046
14.7 psia	Normal Air	Self-extinguishing

accelerations frequently created enough momentary convection to cause the accumulated mass of gases to burn up. This was most pronounced during the null-gravity experiments with pure oxygen.

(6) The increased free convection created by higher gravity level accelerated the burning rate of the cotton cloth specimens. The increase between 3 and 5g was much less than that between 1 and 3g. There appeared to be little difference, from a burning rate standpoint among the selected atmospheric composition for a null-gravity condition if no convection is present. However, the higher convection rates that could be created by the thermal control system, produced during ground checkout as well as during high-g launch or entry conditions, must be considered in the materials selection program. These considerations also apply when selecting the atmospheric composition and procedures used during different mission phases. It is recommended that forced ventilation be used to simulate free convection for elevated-g conditions in materials tests. A 75-fpm forced convection rate is a good design value for testing most materials that are considered to be flammable.

(7) New burning rate test data were obtained for neon-oxygen atmospheric mixtures. The neon-oxygen test points for 5 psia, 7 psia, with 3.5-psia oxygen pressure fell in between the values for nitrogen-oxygen and helium-oxygen, as would be expected based on relative gas thermal conductivity. The burning rate of cotton cloth specimens in pure oxygen at 5 psia was nearly 5 times that of air at 14.7 psia. At 5-psia total pressure with 3.5-psia oxygen partial pressure, the ratio was reduced to 4.5 for helium-oxygen, 3.9 for neon-oxygen, and 3.7 for nitrogen-oxygen. At 7- psia total pressures, the ratios became 3.4 for He/O_2, 3.0 for Ne/O_2, and 2.5 for N_2/O_2.

(8) Overloaded electrical wires took the longest to smoke and/or burn through in helium-oxygen mixtures, as compared to nitrogen-oxygen and neon-oxygen mixtures. Shortest times were observed in pure oxygen.

(9) Effects of diluents (helium, neon and nitrogen) or smoking and burn-through time of overloaded wires were magnified when the wires were bundled.

(10) The decomposition products of cotton cloth other than H_2O, CO_2, and CO were low molecular weight aldehydes, organic acids, and benzenoid ring compounds. These compounds were produced in quantities large enough to be detected by several sensors. A two-wavelength infrared sensor can potentially detect these and all hydrocarbons by sensing for the carbon-hydrogen bond and the carbon-carbon double bond. The materials for each particular spacecraft must be analyzed for degradation products adaptable to rapid fire detection unit design.

(11) Nitrogen or helium diluent will potentially be aboard most long-duration mission spacecraft as part of the atmospheric supply system.

Therefore, gaseous nitrogen or helium were individually evaluated for putting out a small cotton cloth fire. The cloth samples smoked after the flame was suppressed. It is recommended that additional tests be completed with a broader range of materials, using inert diluent for extinguishing small fires. Additionally, a combination of gaseous inert diluents followed by minimal water spray for quenching should be evaluated. Liquid nitrogen may be good for suppressing the flame and quenching the fire for absolute put-out and should be evaluated.

Recommendations

The duration of true zero gravity was intermittent during the KC-135 flights, yielding typically spans of 3 to 5 sec. Tests are required in much longer duration zero g to confirm the data and conclusions of the KC-135 testing. The following areas are of fundamental importance to the safety of manned space operations and should be investigated in sub-orbital or Earth-orbital flight:

(1) Ignition, ignition flash, combustion, and self-extinguishment of various materials, with and without forced convection.

(2) Correlation of spherical flame growth and self-extinguishment to atmospheric composition and material type.

(3) Evaluation if various extinguishing techniques, particularly water and inert gas methods.

(4) Infrared studies of the zero-g flame envelope to aid in the confirmation of mathematical models.

Section 2

TEST CONDITIONS AND PROCEDURES

The effects of atmospheric composition, atmospheric pressure, ventilation rate and gravity level on burning rate and ignition were evaluated. Additionally, test specimen material decomposition products applicable for possible fire detection were analyzed as well as the effectiveness of cabin atmosphere supply inert diluent as a fire extinguishing agent.

The test materials and procedures for determining the relative effect of cabin atmosphere selection on burning rate and ignition temperature were established and reported in detail in NASA CR-891 (ref. 1). The test conditions, test equipment and procedures previously reported are reviewed. New test apparatus and procedures are also described.

Test Specimen

Cotton cloth and insulated wire were selected to determine the effects of atmosphere and gravity on ignition time and burning phenomena. The cloth used was Flight-Tex Grade A (MIL-C-5646C). The cloth samples were 2 in. x 8 in. treated with flame retardant along the 8-in. edges to produce straight line burning. The samples were ignited across one end and the burning rate was measured as the rate of a flame or char propagation along the cloth. The sharp separation of the char and the unburned cloth allowed for ease of measurement of the burning rate.

A series of tests was also conducted to determine the ignition and burning phenomena that could be expected from a single overloaded insulated wire either alone or in a wire bundle. The insulated wire selection procedure is given in ref. 1. It was necessary to select a wire insulation combination that would smoke and burn freely when overloaded. This readily permitted the observation and recording of differences existing between atmospheric compositions. The three test wires used for preliminary testing were (1) a 20-gage wire with white Teflon insulation, Douglas specification 7869679 Class A, nickel-plated Teflon wire; (2) a 20-gage wire with red TFE insulation produced by Hi Temp Wire Co., Monrovia, California; and (3) a 20-gage wire insulated with cross-linked polyalkene and polyvinyledene flouride, produced by the Raychem Corp. The first two wires tested showed no burning of the insulation. In both instances, the insulation curled, peeled off, and dropped to the bottom of the flask, without any smoke formation. By contrast, overloading the third wire resulted first in heavy smoke formation followed seconds later by the burnthrough of the wire itself. Since both phenomena were readily reproducible, this wire was selected for use for future tests.

The cotton cloth specimen was used throughout all burning rate tests to provide a comparison showing the relative effects of atmosphere composition, atmosphere pressure, ventilation rate and gravity level on burning rate and ignition phenomena. A single insulated wire and an insulated wire in a bundle configuration were selected and tested in 1g to show the fire retardation effects of the different atmosphere mixtures and compositions.

Test Conditions

The tests were conducted in atmospheres typical of those proposed for spacecraft cabin usage. Atmosphere compositions included normal air at 14.7 psia, pure oxygen at 3.5 psia and 5 psia, and two gas mixtures of oxygen with a partial pressure of 3.5 added to either helium, neon or nitrogen diluent resulting in total pressures of 5, 7, and 10 psia.

The relative burning rate tests using cotton cloth were performed at null gravity, 1g, 3g, and 5g. The gravity levels were selected as most representative of spaceflight, launch and entry conditions. The spectrum of test conditions for which burning rate data was obtained are shown in Table II.

Burning rate measurements for the cotton cloth were taken with forced ventilation at 50 fpm in null gravity and at 1g. The insulated wire bundle and single wire tests were conducted at 1g with free convection only. The forced convection of 50 fpm was delivered from two positions. One series of tests had the airflow perpendicular to the cotton cloth specimen, and the other parallel to the cotton cloth in the direction of burning. The blowers were calibrated to deliver 50 fpm for each separate atmospheric composition and pressure level when located 6 in. away from the specimen.

Test Equipment

Ignition temperature test apparatus. -- Analysis indicates that ignition temperature should be a unique number for each material and atmospheric composition. Therefore, if the ignition temperature for the test material is known then this parameter can be set for the null-gravity flights, thus eliminating one very important variable. Ignition temperature tests were conducted using a 4-in. x 4.5-in. x 1/4-in, thick copper hot plate and a 4,000-cu-ft-volume Space Cabin Simulator for containing the atmospheric mixture and gas pressure required for the test. The test setup is shown in Figure 1.

Burning rate test apparatus. -- The cotton cloth specimens for burning rate tests were placed in 72-liter pyrex flasks to determine the effect of atmospheric composition and pressure on ignition and burning.

Table II

TEST CONDITIONS

Total Pressure (psia)	3.5	5.0	10.0	16.0	5.0	7.0	10.0	14.7	14.7	5.0	7.0	10.0
Gas Mixture												
$\%O_2$	100	100	100	100	70	50	35	24	Air	70	50	35
$\%N_2$	0	0	0	0	30	50	65	76		0	0	0
%He	0	0	0	0	0	0	0	0		30	50	65
Gravity (Gs)												
0	X	X			X	X			X	X	X	
0.16						X						
0.30						X						
1.0	X	X	X	X	X	X	X	X	X	X	X	X
3.0	X	X			X	X	X	X	X	X	X	X
5.0	X	X			X	X	X	X	X	X	X	X

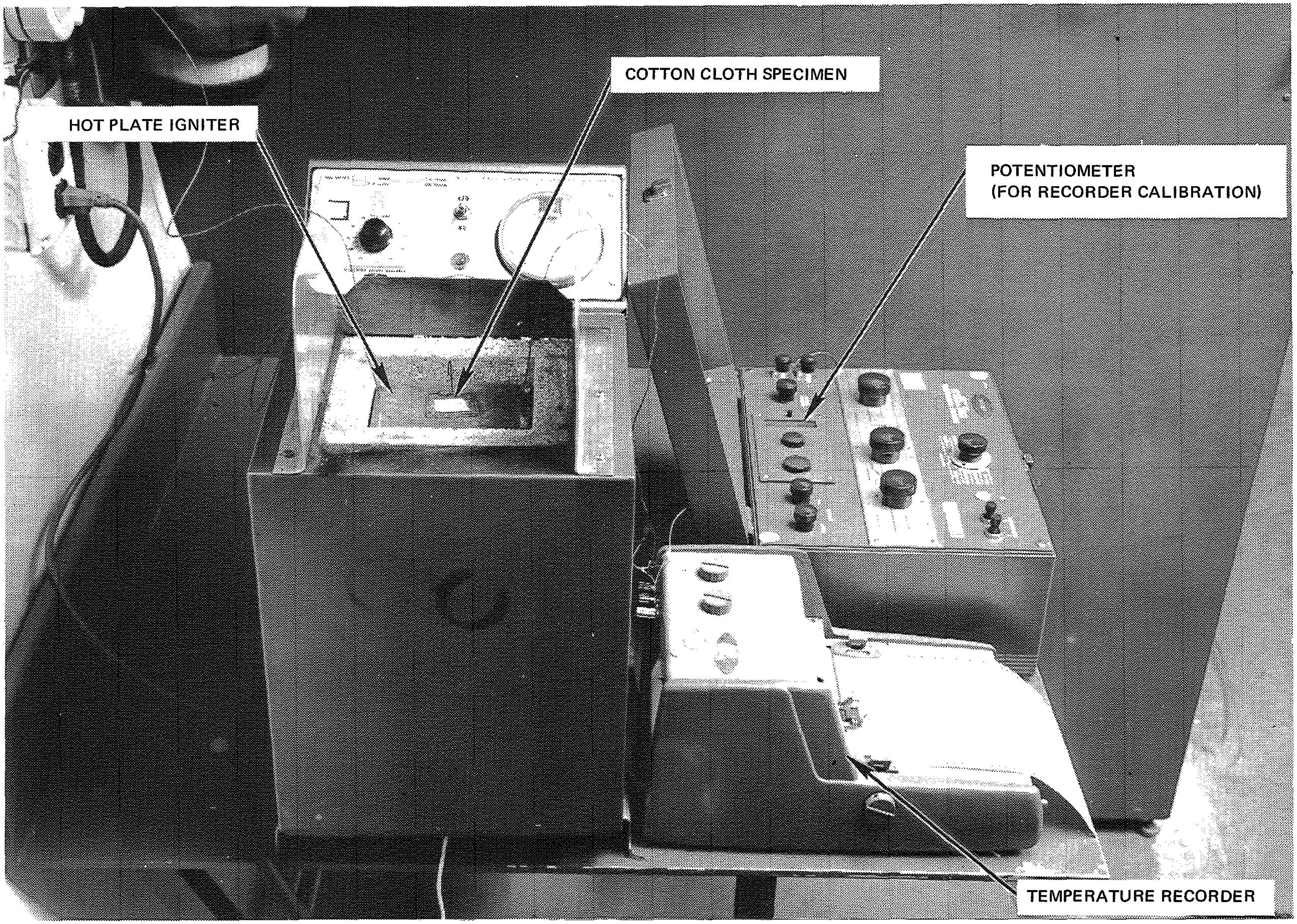


Figure 1. Ignition Test Apparatus inside the Space Cabin Simulator

Figure 2 shows the test apparatus for cotton cloth tests. The large volume of the 72-liter flasks ensured that the atmospheric oxygen remained substantially constant throughout the test.

The test apparatus used in testing the insulated wire specimen is illustrated in Figure 3. A 12-in. length of wire was installed in the circuit between the two low-resistance copper terminals. A constant current of 50A at a voltage of 1.0 to 1.5V was used. The atmospheric composition and pressure level conditions previously used for cotton cloth tests were repeated for the wire insulation test. Nitrogen, helium, and neon were used as diluents. The desired atmosphere was established within the bell jar after placing the selected wire in test position, as shown in Figure 3. The partial pressure of oxygen was kept constant at 3.5 psia, while total pressures from 4.1 to 14.7 psia were produced by the addition of helium, neon, or nitorgen. In the case of pure oxygen, the required amounts of oxygen were introduced into an evacuated bell jar. The experiment was then activated by applying 50A to the electrical wire. This input was maintained until time readings of smoke density and burnthrough had been reported.

The same Raychem electrical wire used for the testing of individual wires was also used in the preparation of wire bundles. Each bundle consisted of seven wires; the current-carrying wire was 12 in. long, the other six wires were 1/8 in. shorter at each end. The current carrying wire was located at the periphery of the bundle rather than its center. A few exploratory experiments indicated that the position in the bundle of the current-carrying wire greatly affects the burning characteristics of the entire unit. The peripheral position was selected because it permitted the greatest area contact with the atmosphere. All measurements taken during these tests were identical to the single-wire test procedure.

Null-gravity and elevated-gravity test equipment.-- The various gravity levels were achieved in three ways. One g was obtainable, of course, in the laboratory. Controlled gravity levels of 2 to 5g's were produced by a 10-ft radius centrifuge, as shown in Figure 4. Null gravity was achieved by flying Keplerian trajectories of about 20 sec each in a KC-135 aircraft as shown in Figure 5. The elevated- and null-gravity tests were performed to determine the relative burning rate of the cotton cloth specimens in different atmosphere compositions specified under the design conditions. The 72-liter flasks were used in the tests.

Figure 6 shows the support and the cotton cloth specimen for the null-gravity tests. A stainless steel wire grid supports the cloth impaled on the upturned ends of the grid's cross pieces. The Nichrome ignition wire is underneath the cloth at the left end. The blower shown provided forced convection at 50 fpm, when required, and was calibrated for all the atmospheres used. Figure 7 shows the sample in the test fixture. The large volume flask

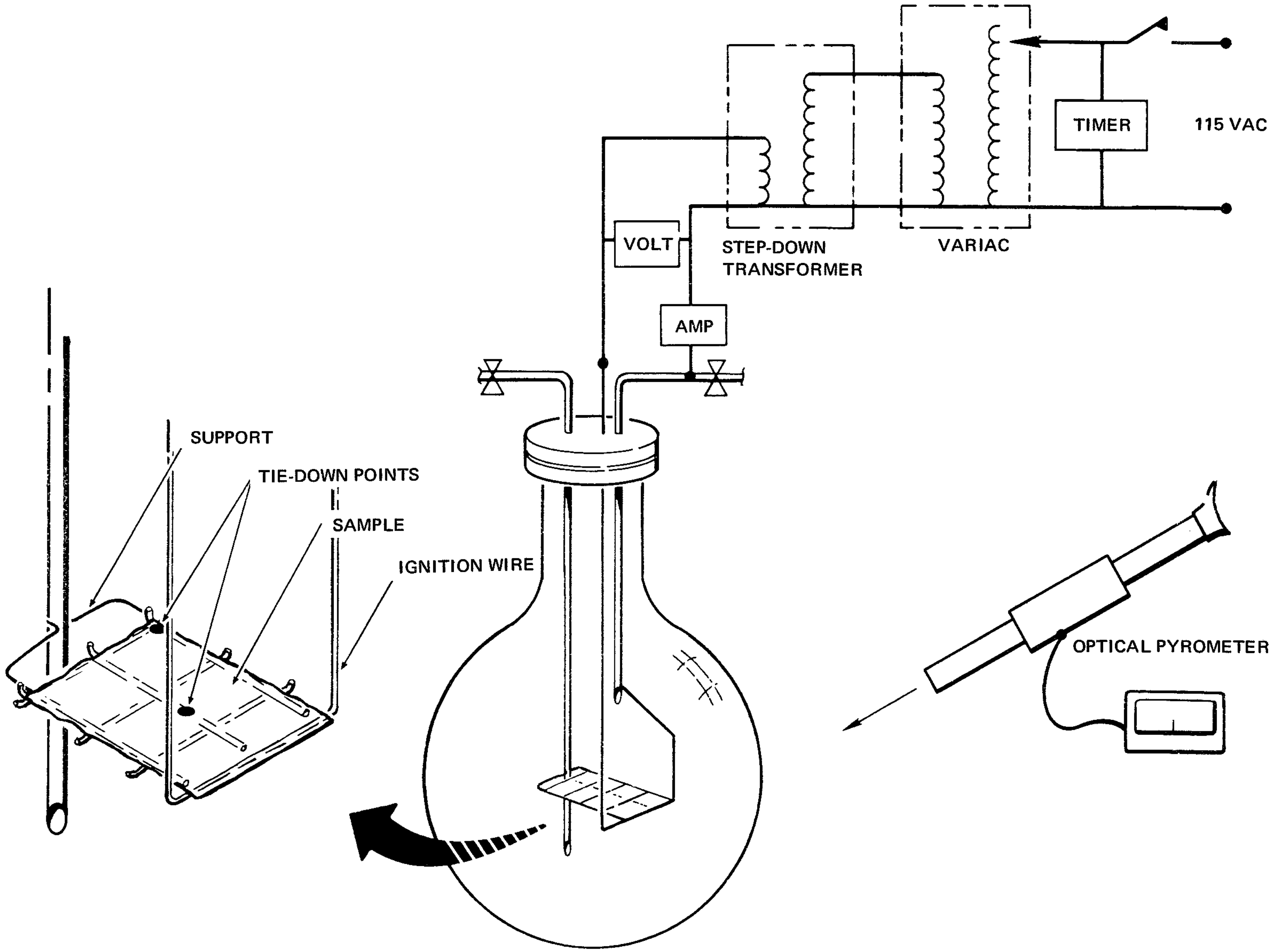


Figure 2. Burning Rate Test Apparatus for Cotton Cloth

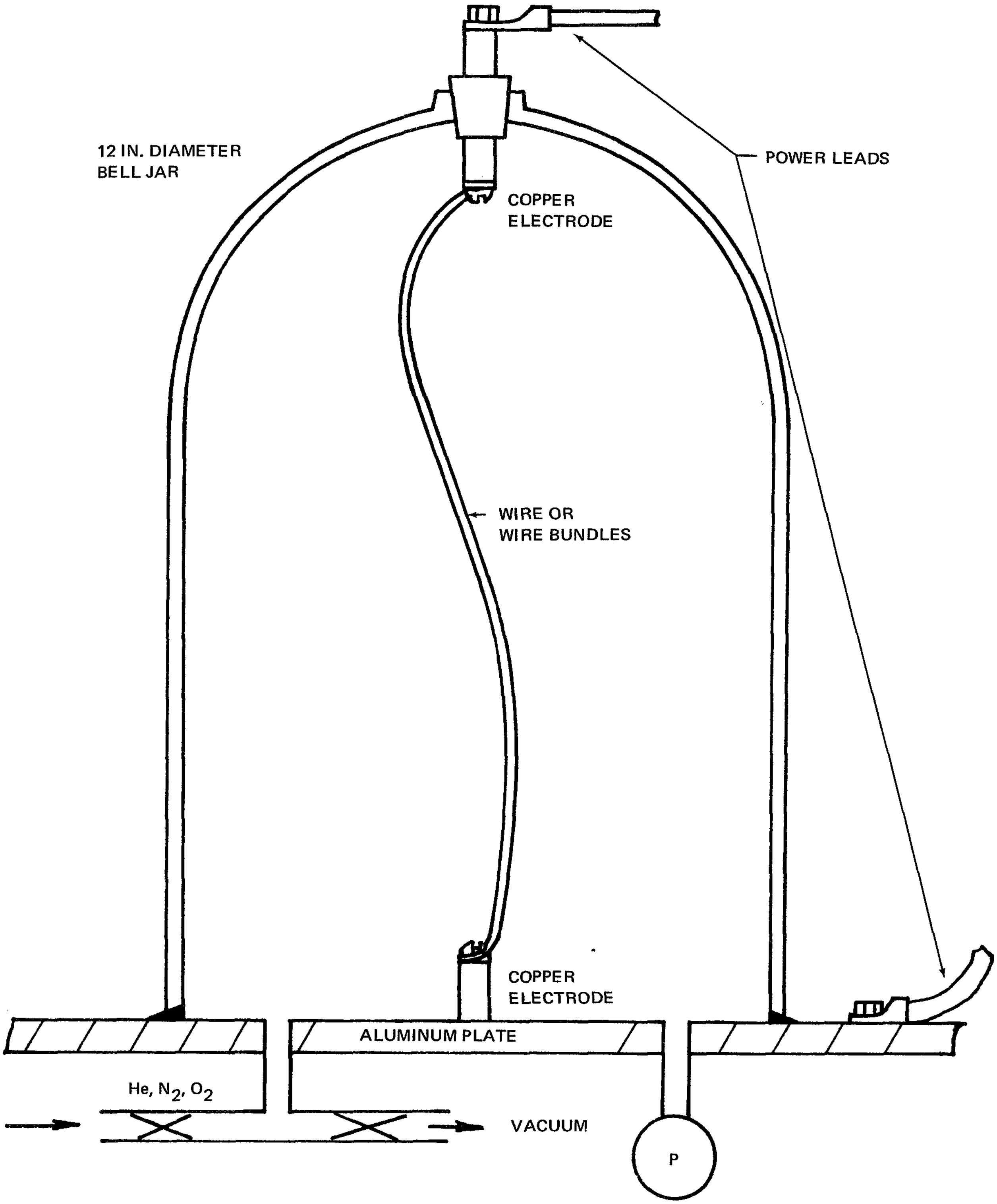


Figure 3. Bell Jar and Wire Test Apparatus

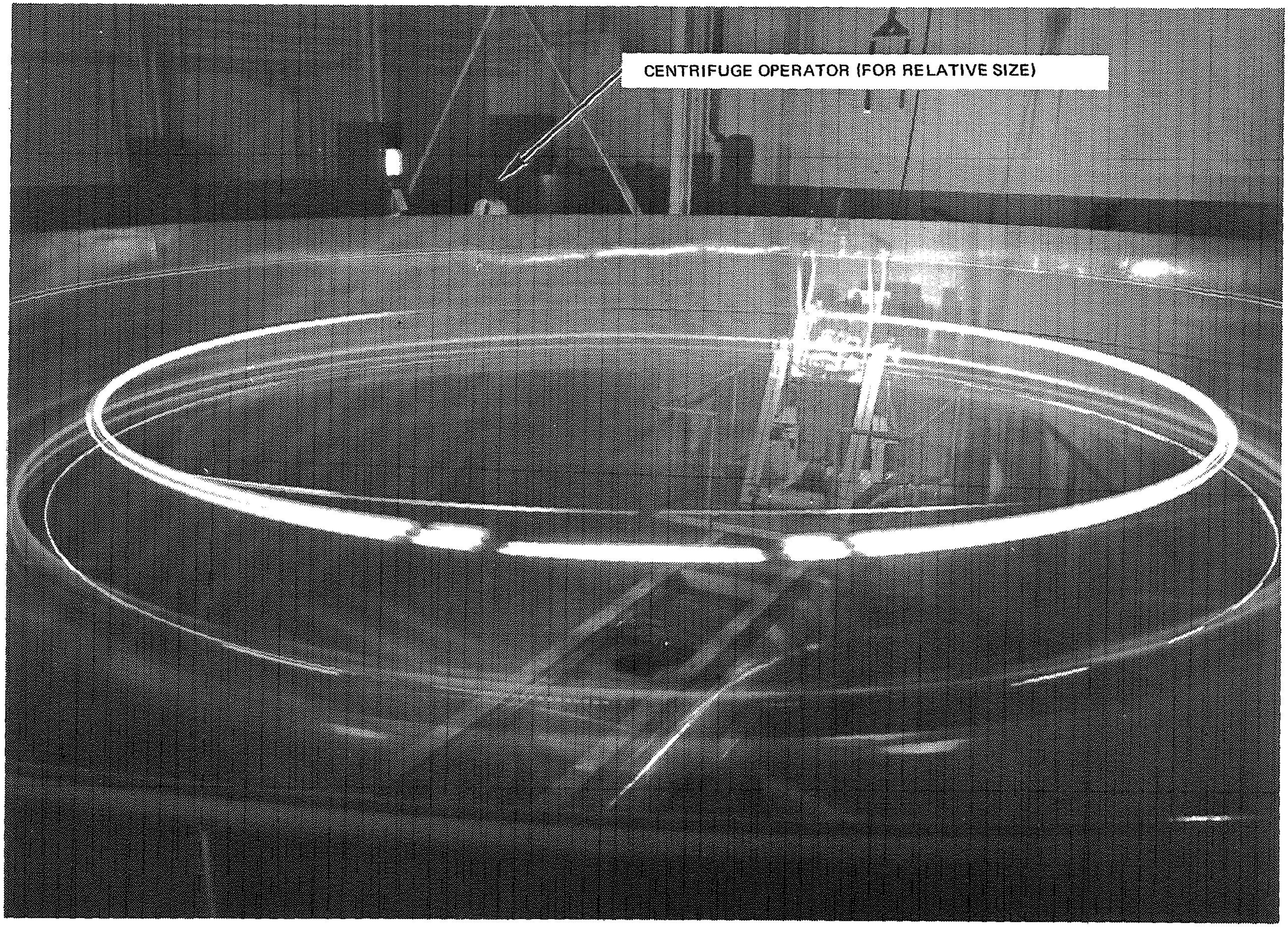


Figure 4. Centrifuge used for Elevated-Gravity Testing

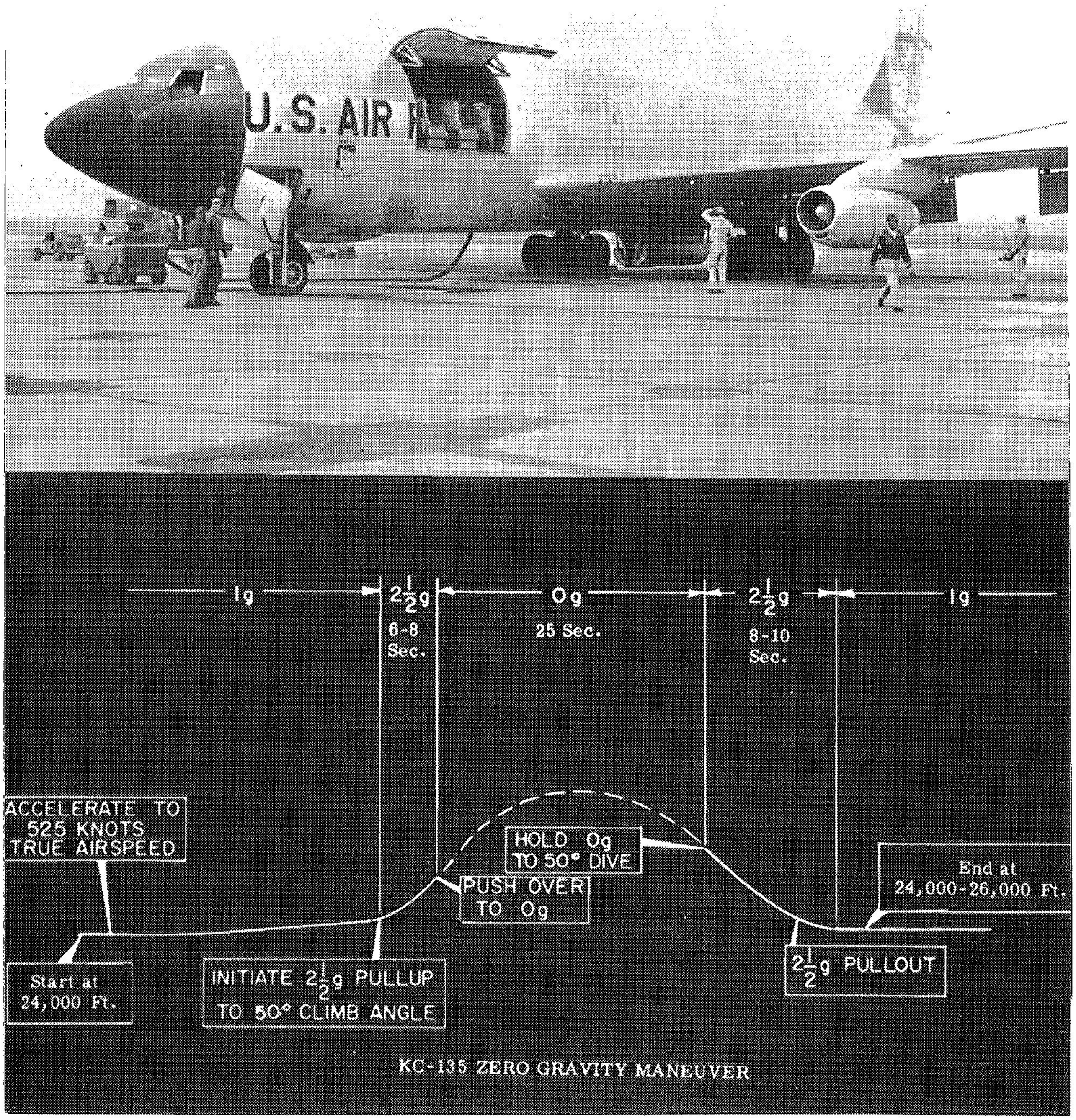


Figure 5. KC-135 Aircraft used for Null-Gravity Testing

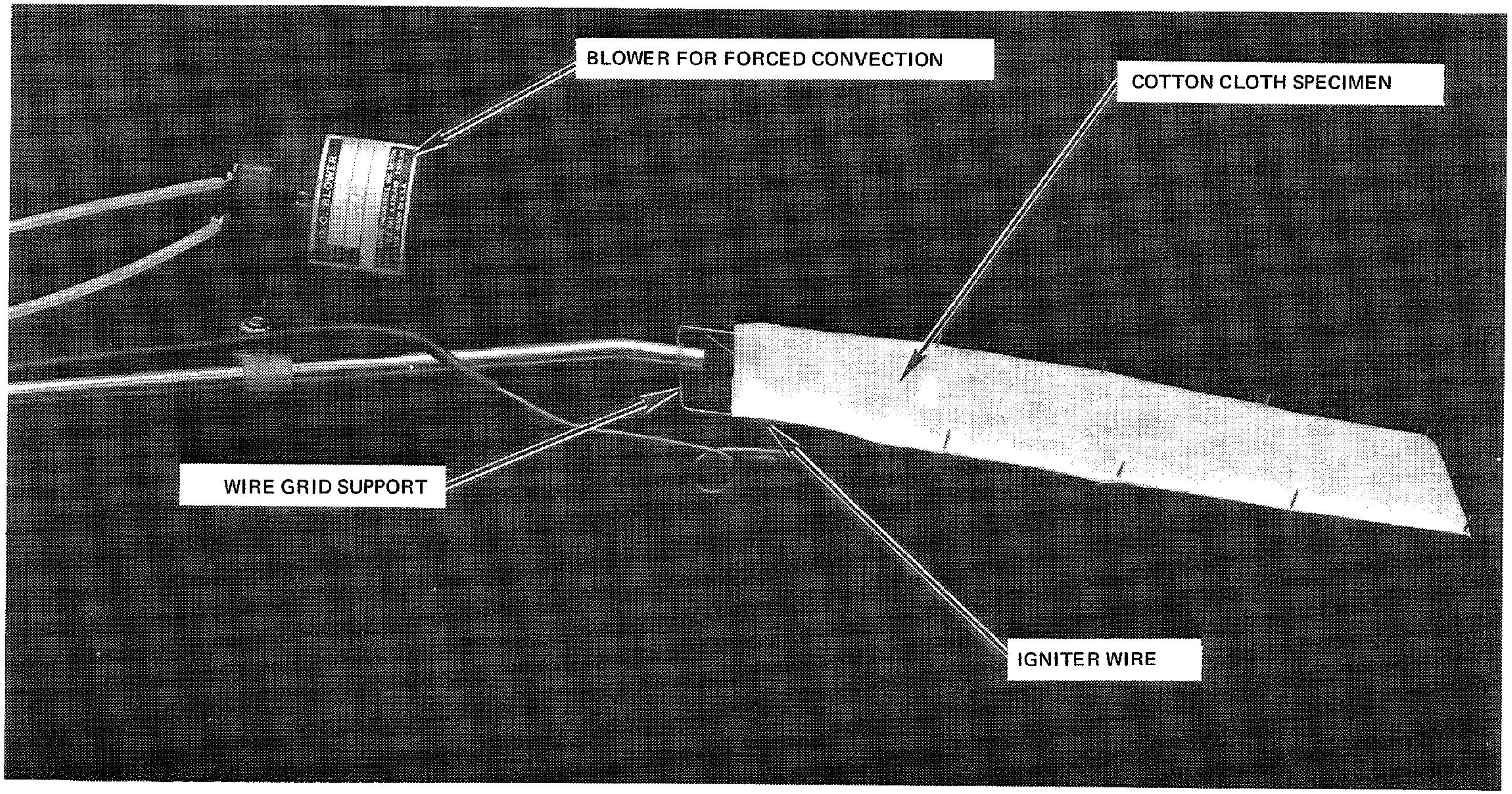


Figure 6. Cotton Cloth Specimen and Support for Null-Gravity Testing

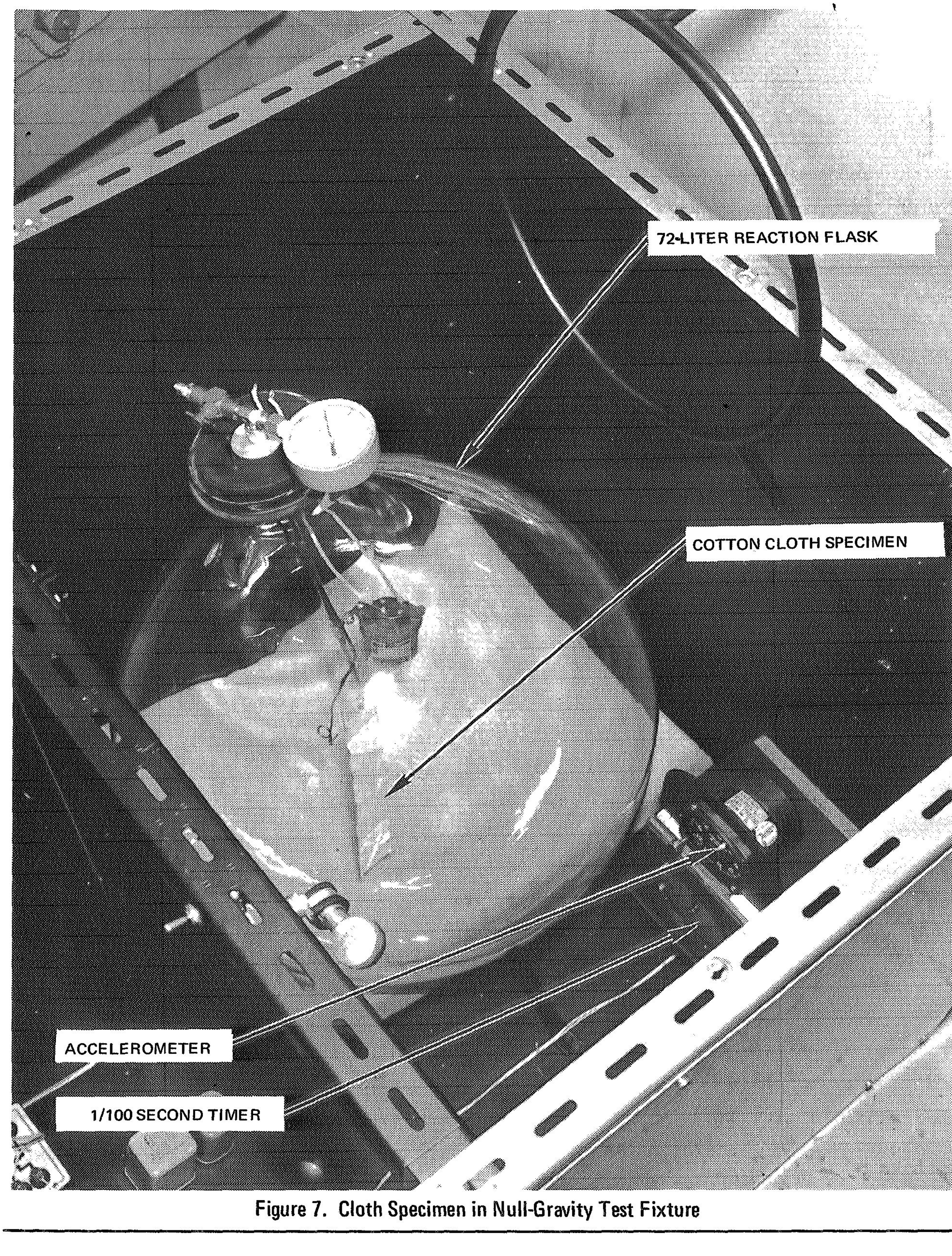


Figure 7. Cloth Specimen in Null-Gravity Test Fixture

(72-liter) was again used to prevent a substantial change in atmosphere composition during burning. The test fixture incorporated a Milliken (DPM-4/EP) high-speed 16-mm motion picture camera with a wide-angle lens. A mechanical accelerometer and an electric timer were in the field of the camera.

Combustion products sampling apparatus.-- Figure 8 shows the sampling unit that was used to collect cotton cloth pre-ignition and post-ignition products of combustion prior to intermixing. A bell jar baseplate was modified to accept two sample collection units. The cloth specimen was mounted as shown.

Cotton cloth samples were burned in space cabin atmospheres to allow collection and analysis of the products of pyrolysis prior to ignition, and of combustion subsequent to ignition. A cloth specimen was mounted close to the baseplate, the atmosphere was prepared, and the igniter wire was energized. Two tubes were placed directly above the cloth for sample collection. The tubes passed through the baseplate to evacuated 1-liter gas bottles, which permitted sample collection from the reduced pressure bell jar atmosphere. The pre-ignition sample bottle was opened when the smoke evolution reached a predetermined rate (visually observed). The normal time was 3 sec for a 1035°C igniter wire. The bottle used for post-ignition samples was opened when combustion was almost complete to allow collection of the products at maximum concentrations. A septum assembly attached to each bottle was used for evacuation and allowed collection of the samples in hypodermic syringes for introduction into a gas chromatograph. Positive identification of the compounds present was accomplished by analyzing the sample with two different chromatographic columns, each operated at 50°C and 100°C, thereby providing four elution times per compound.

Inert gas flooding apparatus. -- A series of tests was performed to evaluate the effectiveness of several techniques of fire extinguishment by inert gas flooding. Horizontal 2-in. x 8-in. cotton cloth specimens were ignited in pure oxygen atmospheres at 3.5 and 5 psia, in a bell jar, shown in Figure 9. Inert gas was admitted into the bell jar, aimed both indirectly and directly at the burning cloth. The nozzle assembly shown in Figure 9 provided the most rapid extinguishment.

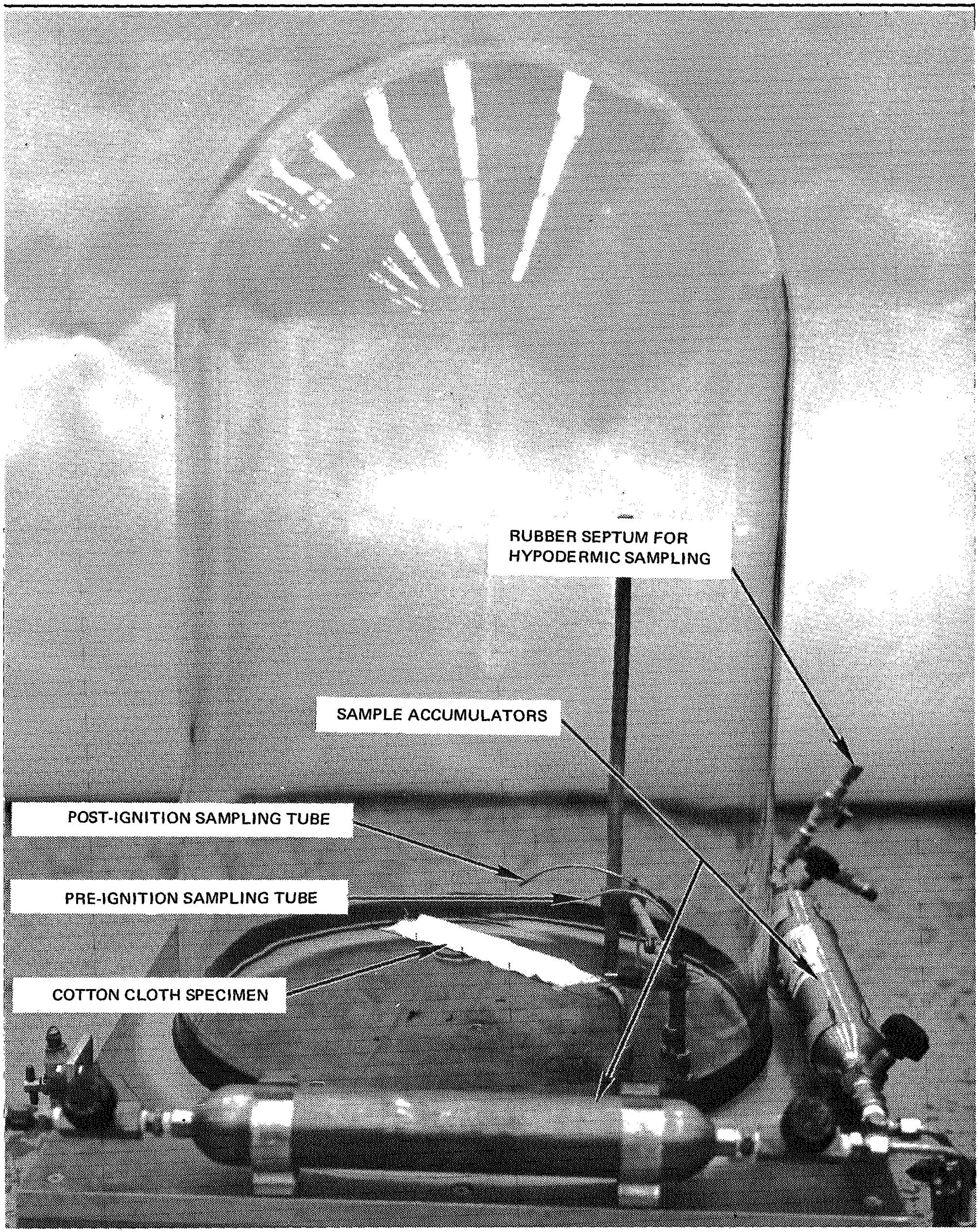


Figure 8. Decomposition Products Collection Apparatus

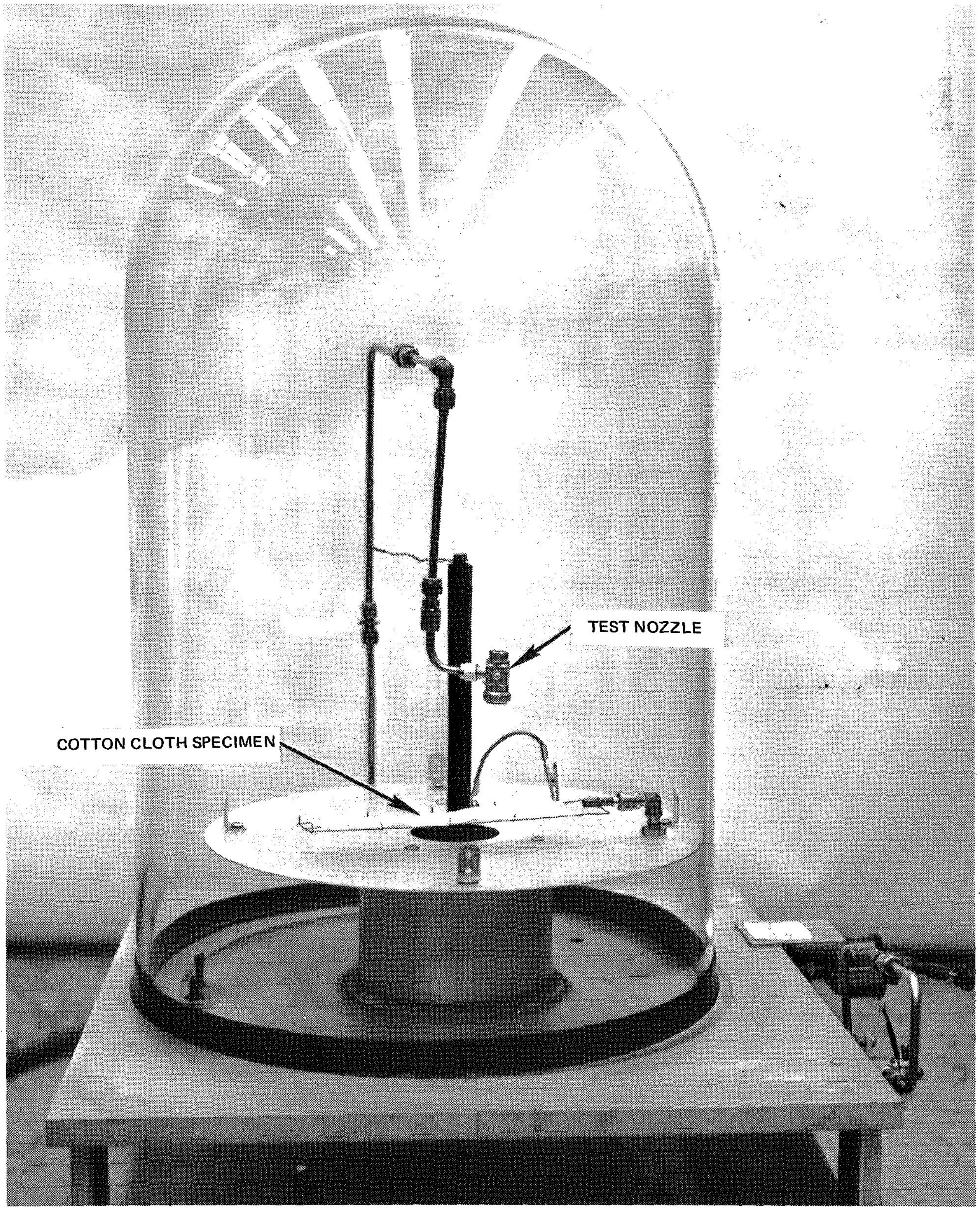


Figure 9. Inert Gas Flooding Test Apparatus

Section 3

EFFECTS OF ATMOSPHERE COMPOSITION AND GRAVITY LEVEL UPON IGNITION

Analysis indicated that ignition temperature should be a unique number for each material and atmosphere composition. The ignition temperature is essentially independent of the amount and nature of atmosphere diluent but is dependent on oxygen partial pressure, as shown in Figure 10. The ignition temperature of cotton cloth decreased as the oxygen partial pressure in the atmosphere was increased. For example, the ignition temperature was lowered from 630°C at 3.5 psia oxygen partial pressure to 550°C at 5 psia pure oxygen for the cloth sample tested. From a fire prevention standpoint, it would be advisable to increase ignition temperature by lowering the oxygen partial pressure to a minimum. The power required to reach the ignition temperature is not significantly higher in ambient sea level air than in pure oxygen atmospheres at 3.5 and 5 psia. The power input required to reach the same operating temperature is considerably greater using helium as a diluent than when using nitrogen.

Tests indicated that minimum ignition temperature is dependent on the type of material. The minimum ignition temperature is affected very little by gravity and forced ventilation. For cotton cloth, the ignition temperature was 650°C ± 10°C and for the insulated wire 700°C ± 20°C for all typical pressures from 5 psia to 14.7 psia with a 3.5-psia oxygen partial pressure in both nitrogen-oxygen and helium-oxygen mixtures. The establishment of ignition temperature determines one important parameter for the null-gravity tests.

Gravity indirectly affects heat transfer rate through bouyancy forces. However, gravity should have no effect upon ignition temperature (ref. 1). Convective velocity and gas pressure will influence the heating rate and dilute the combustible gas but should have very little effect upon the ignition temperature. Kimzey also recognized that the ignition phenomena differences between no convection in null gravity and free convection at 1g is relatively small (ref. 3).

The effect of increased gravity on ignition time is shown in Table III. The values are shown for the different atmospheric compositions. The effect of the gravity level and 50-fpm ventilation rate at 1g on ignition time was minimal, as shown on Table III. Ignition time was expected to be significantly increased at elevated g's and for the forced ventilation case because of the cooling effect of the convective forces. However, the constant

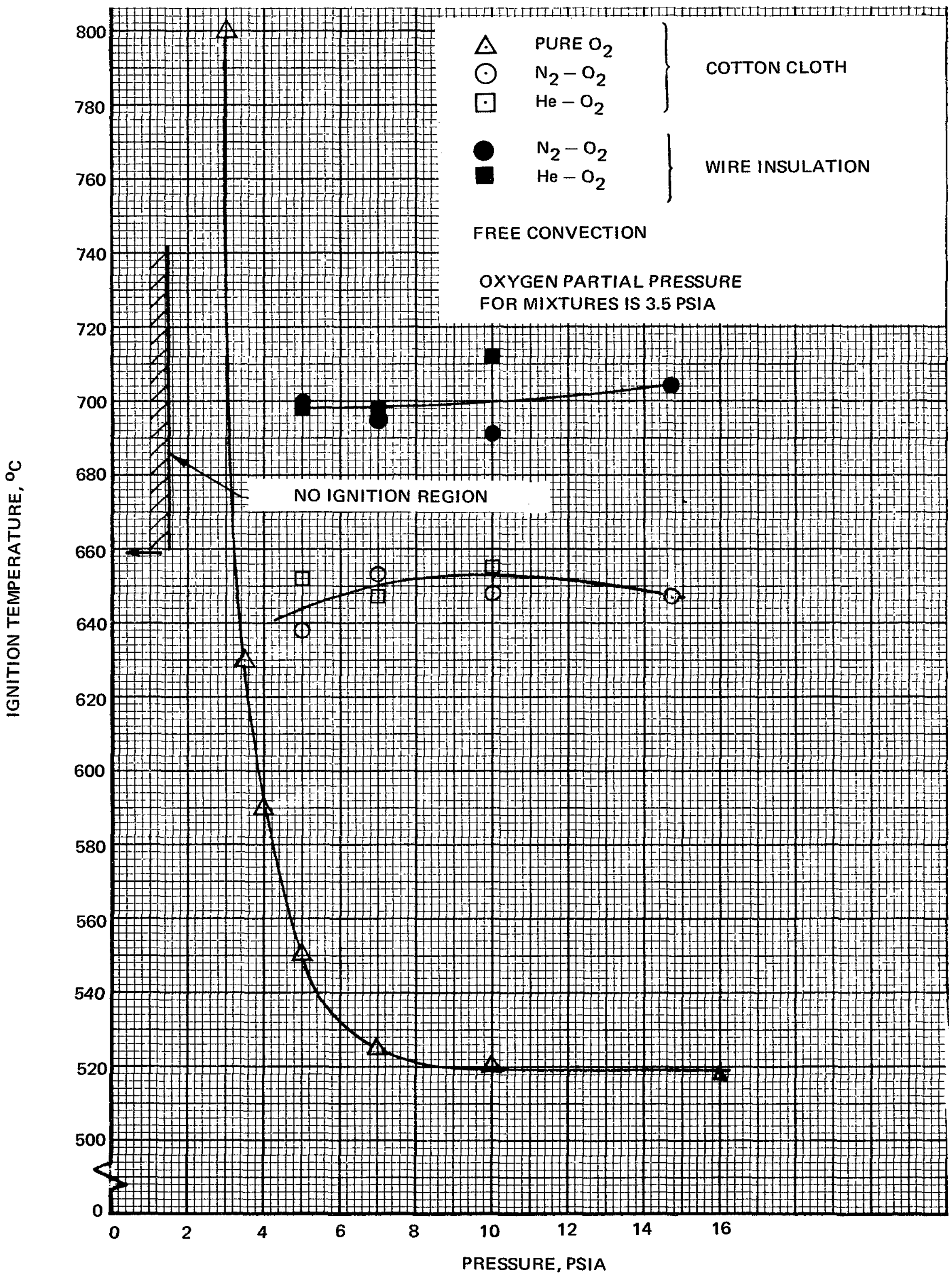


Figure 10. Ignition Temperature of Cotton Cloth and Insulated Wire

Table III

THE EFFECT OF GRAVITY UPON THE TIME TO IGNITE COTTON CLOTH

Atmosphere		Wire Temp. (°C)	Ignition Temp. (°C)	Average Ignition Time (seconds)			
				Free Convection			50 FPM Forced Convection at 1g
Pressure	Composition			1g	3g	5g	
3.5 psia	100% O_2	1035	630	7.5	5.5	6.0	7.0
5.0 psia	100% O_2	1035	551	5.5	5.3	4.3	5.2
5.0 psia	70% O_2 30% He	880	650	8.1	6.7	7.2	7.0
5.0 psia	70% O_2 30% N_2	1035	641	6.6	6.0	5.3	6.2
7.0 psia	50% O_2 50% He	880	653	10.2	8.0	8.8	9.4
7.0 psia	50% O_2 50% N_2	1035	650	6.3	6.7	5.8	6.0

resupply of "fresh oxygen" probably overcame the cooling effects. Table III presents additional comparison of the effect of free and forced convection on ignition time for various atmospheric compositions and pressure levels.

Ignition at 1g and above is characterized by the appearance of flame and the disappearance of smoke. When this occurs in null gravity without forced convection, it is accompanied by a flash, which is attributed to the rapid burning of the visible cloud of combustibles that are released when the specimen is heated. These combustibles accumulate around the heated area in 0g, as very little convection is present to disperse them. Figure 11 shows the ignition flash occurring in oxygen, helium-oxygen, and nitrogen-oxygen. The film frames are 1/64 sec apart. The total ignition flash occurs in 0.025 to 0.032 sec.

Flash ignition of the combustible gases resulted for oxygen, helium-oxygen, nitrogen-oxygen, and neon-oxygen mixtures in nearly all tests when forced convection was not present. The ignition flash was more confined at the higher gravity levels.

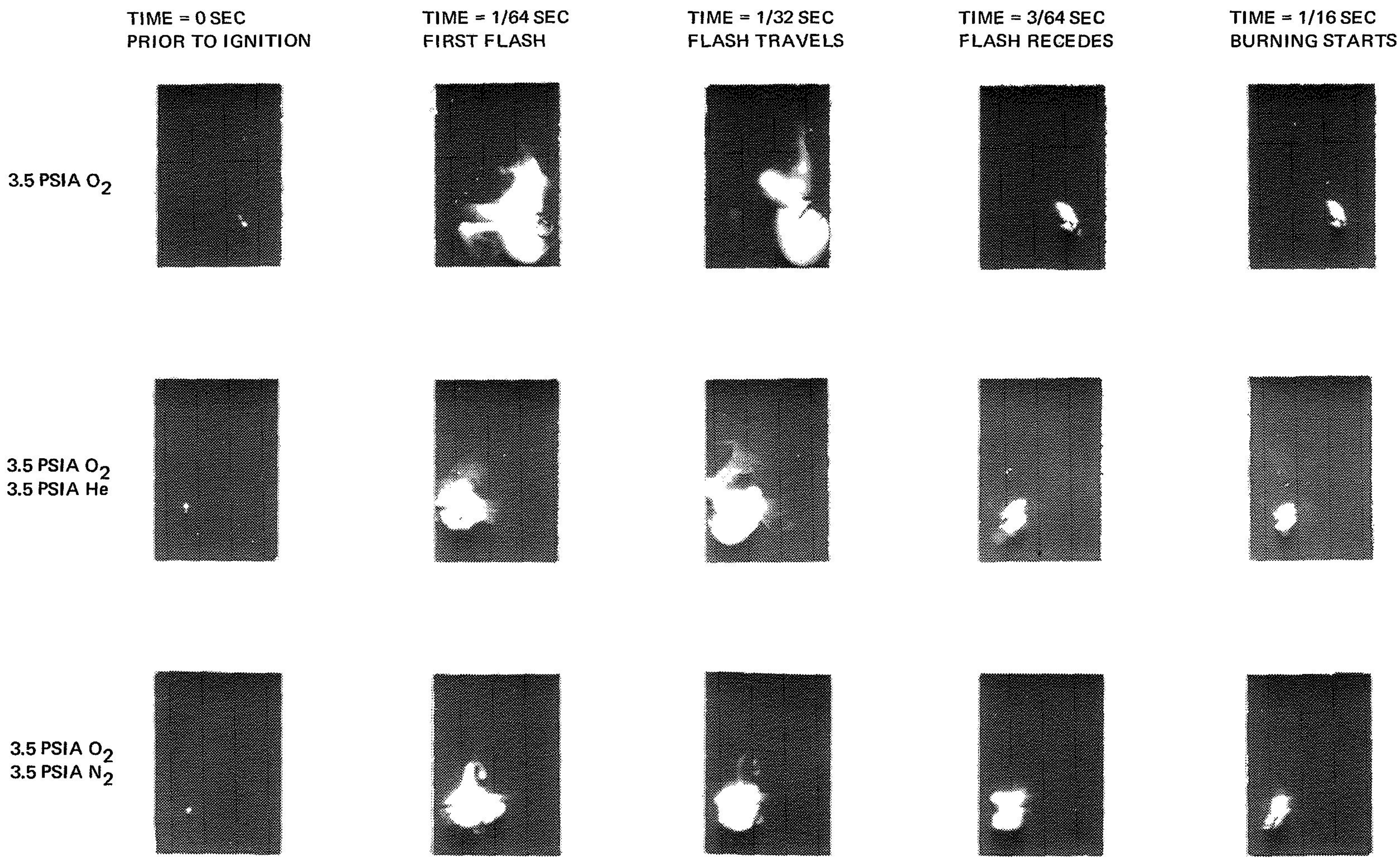


Figure 11. Ignition Flash in Null Gravity

Section 4

EFFECTS OF ATMOSPHERE COMPOSITION AND GRAVITY LEVEL ON BURNING RATE

One-g cotton cloth tests and preliminary null-gravity flight tests in an Aerocommander were completed and reported in ref. 1 for both the helium-oxygen and nitrogen-oxygen atmospheric compositions. The test procedure developed in ref. 1 established a common test specimen that could be used to evaluate the effect of atmosphere composition and gravity level on burning rate. The information reported below presents the additional items required to augment the previously completed tests:

- The effect of null gravity and elevated gravity on the burning rate of the standard cotton cloth specimen.
- The effect of neon diluent on burning rate in 1g as compared to helium or nitrogen.
- The measurement of the degradation products of the cotton cloth, other than CO, CO_2 and H_2O, that could possibly be used for a fire warning system.
- The evaluation of the effectiveness of nitrogen and helium gas forced spray as a fire extinguishing agent.

Burning Rate of Cotton Cloth at Null Gravity and Elevated Gravity

Figures 12 and 13 illustrate the effect of gravity level from that near zero to a 5-g level on cotton cloth burning rate. Convection increases with increased gravity, resulting in higher burning rates for each separate atmospheric composition and pressure level. The burning rate levels at about the 3-g level could be used as a criteria in design. A 50-fpm forced ventilation parallel to the cloth in null gravity produced a burning rate nearly equal to a free-convection 1-g case for 3.5-psia pure oxygen, as shown in Figure 14.

Figure 15 illustrates the relative effect of gravity level from null gravity to five times gravity on cotton cloth relative flame height in a 5-psia environment of pure oxygen; nitrogen-oxygen with 3.5-psia oxygen partial pressure and helium-oxygen with 3.5-psia partial pressure of oxygen. Figure 16 for 5-psia nitrogen-oxygen in null gravity shows the disappearance of the "luminous flame" that occurred for test atmospheres when true zero g was achieved. The flame is bright and globular in Figure 16a but becomes

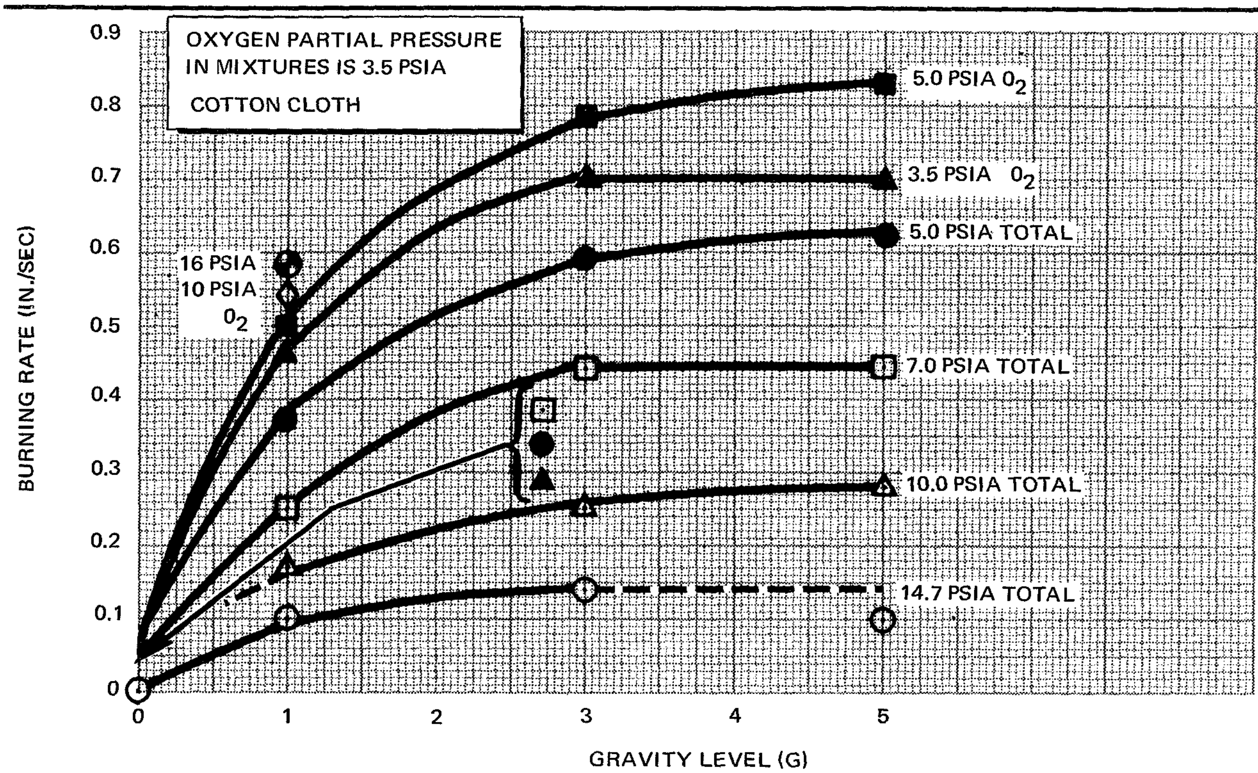


Figure 12. The Effect of Gravity upon the Burning Rate in Nitrogen-Oxygen Mixtures

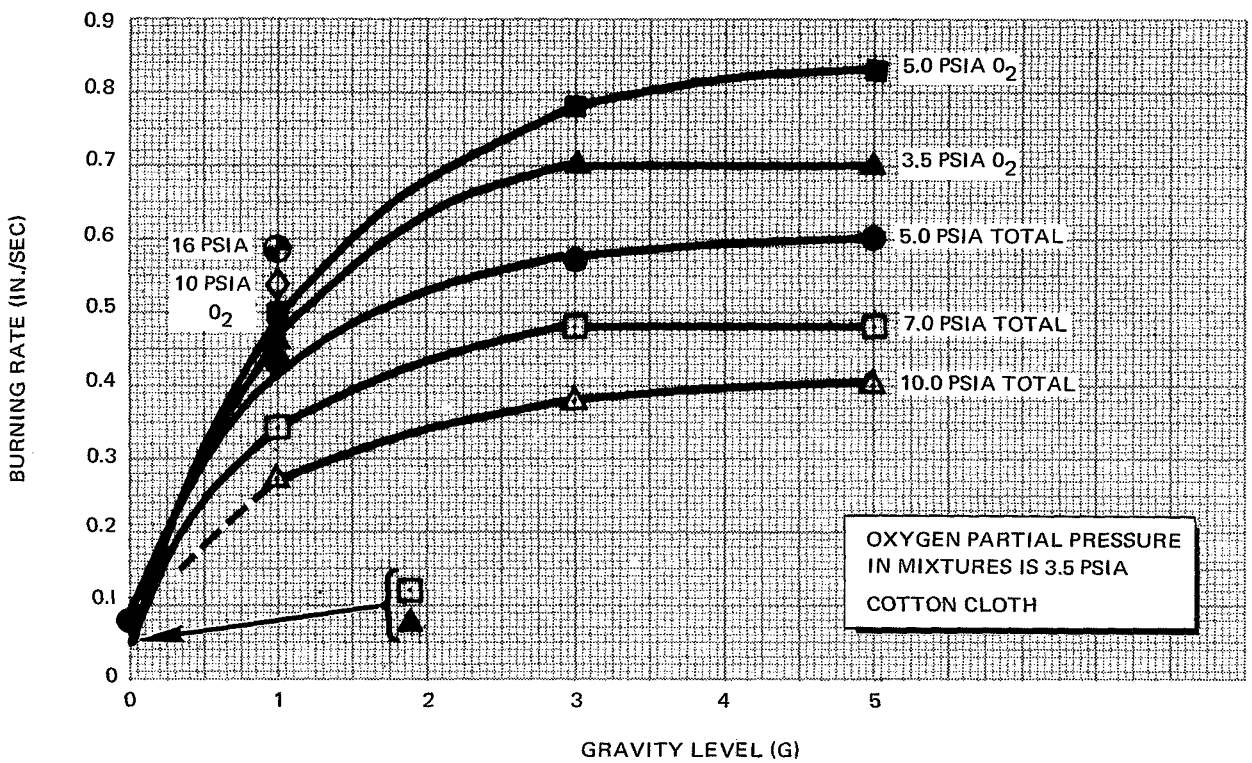


Figure 13. The Effect of Gravity upon the Burning Rate in Helium-Oxygen Mixtures

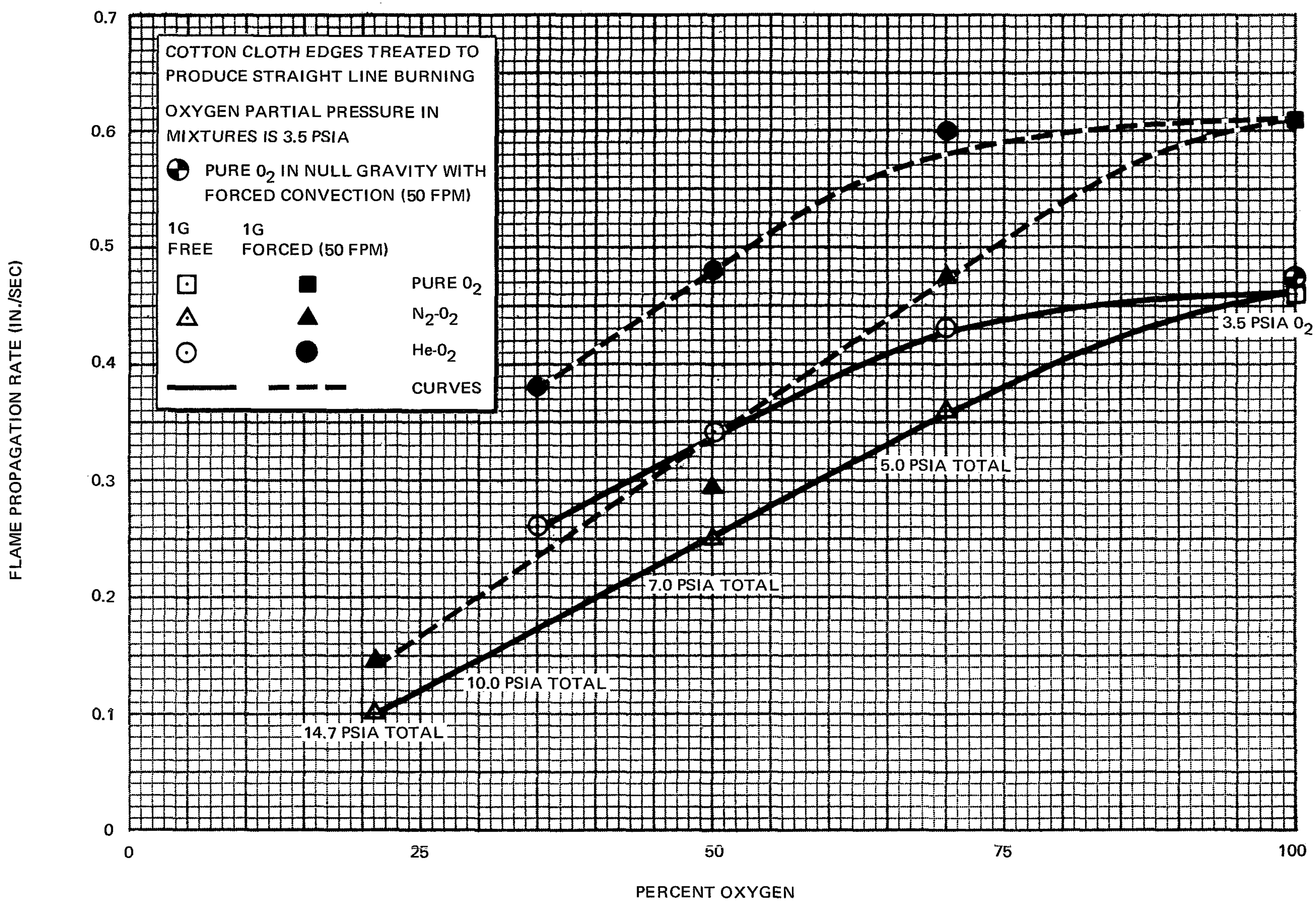


Figure 14. The Effect of Forced Convection upon Flame Propagation Rate

	5.0 PSIA O_2	5.0 PSIA TOTAL 3.5 PSIA O_2 1.5 PSIA He	5.0 PSIA TOTAL 3.5 PSIA O_2 1.5 PSIA N_2
NULL GRAVITY			
GRAVITY LEVEL = 1g			
GRAVITY LEVEL = 5g			

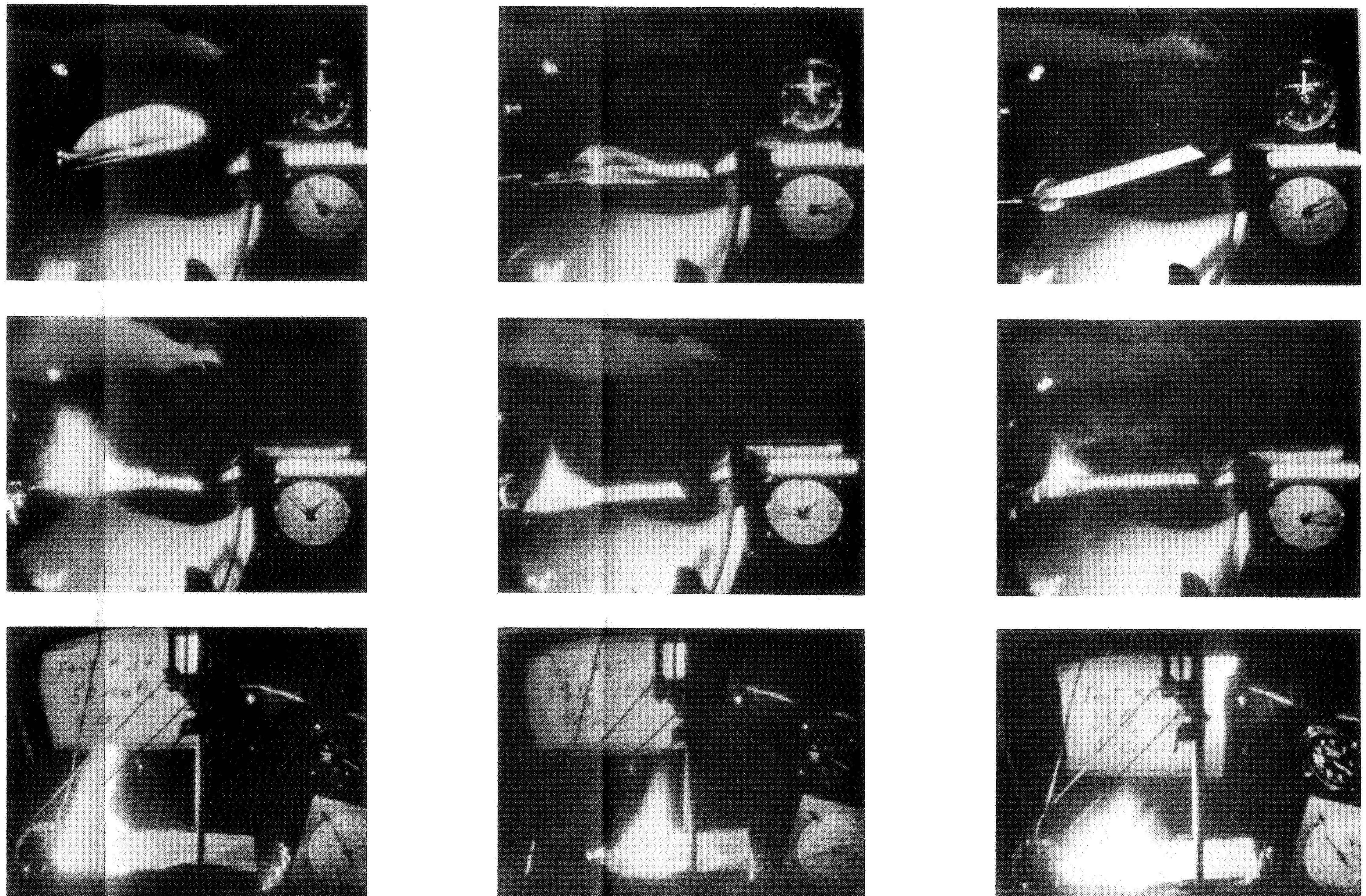
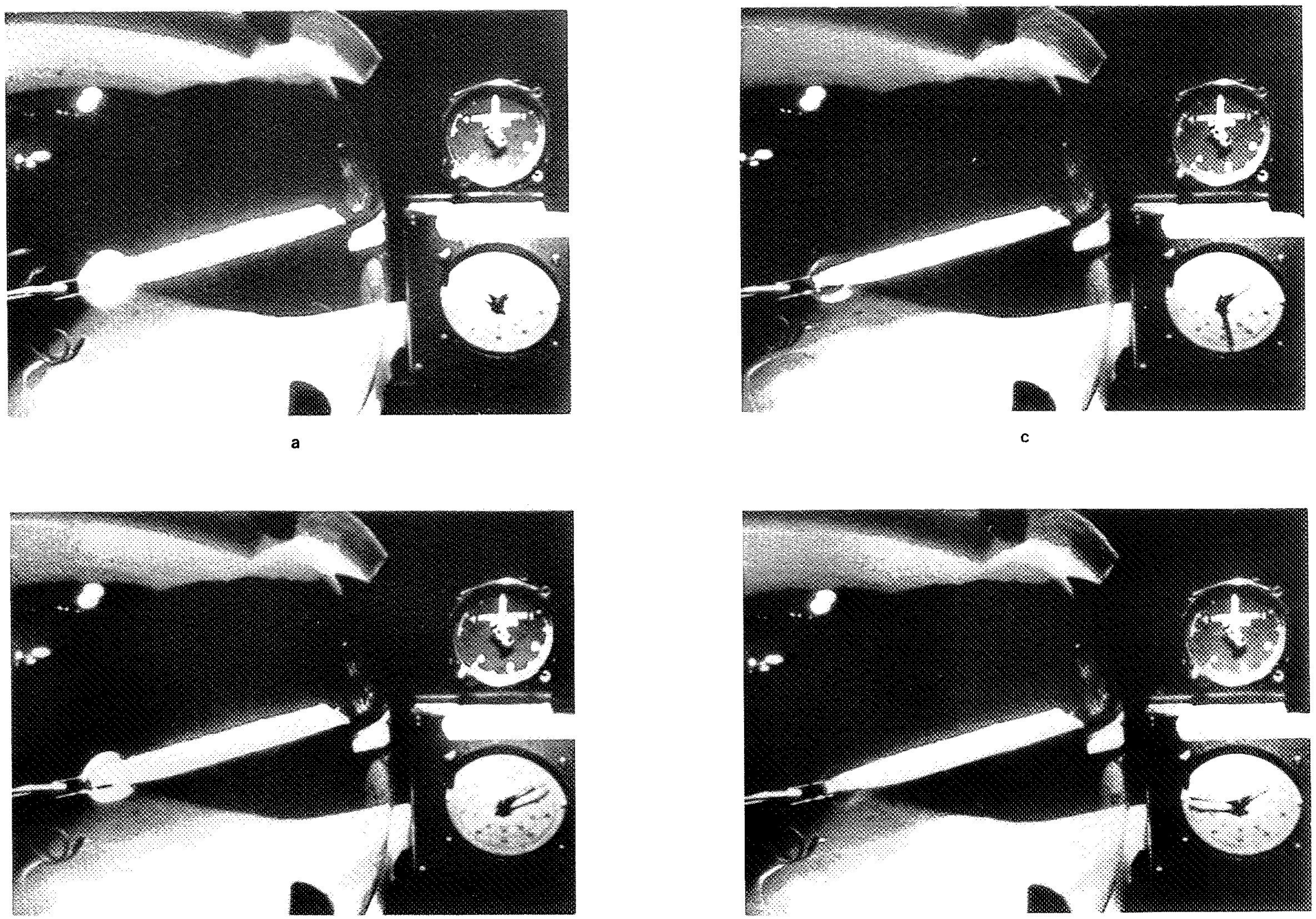


Figure 15. Relative Flame Height at Different Gravity Levels



a c b d

Figure 16. Flame Behavior at Zero Gravity

smaller and dimmer in Figures 16b, 16c, and 16d as gravity level approaches near zero. The char line propagated but no visible flame could be seen for the short period of time in null gravity. The photographs are 1/4 sec apart.

Free convection aids diffusion in supplying oxygen to the flame in gravity. At the high gravity levels, there is an accentuation of the difference between the densities of the hot gases from the fire and the cold gases of the free atmosphere, resulting in higher convective rates and flame propagation rates than at 1g, as shown in Table IV.

Combustion is a combination of heat transfer and mass transfer processes. If convection is present, the mass transfer process is aided. This convection may be self-generated in a normal gravity field, supporting rapid combustion. However, in null gravity, free convection does not occur, convection stops, and the hot combustible gases travel by expansion in all directions from the hot portion of the specimen. When an oxygen molecule attempts to diffuse from the free atmosphere into the combustion zone, it is opposed by the hot gases that expand outwardly from this zone. These hot gases contain both the hot unreacted gases from the specimen and the hot combustion products. The unreacted gases are still present because they cannot come in contact with oxygen until this confrontation takes place. The region at which this occurs is the flame front. As the volume of the hot gases increases, the flame front is pushed away from the specimen. It then appears as a fiery surface that surrounds the expanding volume of hot gases. This spherical flame is characteristic where available oxygen is supplied only by diffusion.

The propagation rate of a flame was very low in null gravity. The rates for cotton cloth near null gravity were between 8 and 18% of those for the same atmosphere in 1g. The experimentally determined null-gravity propagation rates are given in Table V. The burning rates were measured entirely from the propagation rates of the char fronts, as the flame envelope was invisible. The rate for 5-psia oxygen is not stated because the char front did not move in zero g. The spherical flame extended rapidly, charring the edges of the specimen as it moved. During this test, the entire mass of gases burned at the first extraneous acceleration, consuming the entire sample.

For each atmosphere tested, there was a leveling off of the increase in propagation rate when the gravity level rose above 3g. Beyond this point, no significant increase was noted. The rates exhibited at 5g were the highest in each atmosphere and the condition of 5-psia 100% O_2 at 5g was most severe, being 10 to 20 times the zero-g rates at the various atmospheres.

One-g or elevated-gravity tests can be used to help predict null-gravity and forced ventilation effects upon burning rate of most materials without undergoing the expense of null-gravity tests.

Table IV

THE EFFECT OF GRAVITY UPON BURNING RATE OF COTTON CLOTH

Atmosphere		Burning Rate (in. /sec)			
Pressure	Composition	0g	1g	3g	5g
3.5 psia	100% O_2	0.039	0.46	0.70	0.70
5.0 psia	100% O_2	***	0.50	0.78	0.83
5.0 psia	70% O_2 30% He	0.081	0.44	0.57	0.60
5.0 psia	70% O_2 30% N_2	0.043	0.37	0.59	0.62
7.0 psia	50% O_2 50% He	0.052	0.34	0.48	0.48
7.0 psia	50% O_2 50% N_2	0.046	0.25	0.44	0.44

***Not Measurable

Relative Burning Rate of Cotton Cloth in Neon Diluent at 1 g

The new test data for atmospheres containing neon diluent is compared to atmospheres containing nitrogen and helium. As shown in Figure 17, the burning rate of the horizontally positioned cotton cloth, with treated edges for straight line burning, in oxygen at 5 psia is nearly 5 times that in air at 14.7 psia. At the same total pressure, the ratio is reduced to 4.25 for helium-oxygen, 3.9 for neon-oxygen, and 3.7 for nitrogen-oxygen with 3.5 psia partial pressure of oxygen. Figure 18 presents the burning rates data for atmosphere compositions evaluated at 1g. Figure 14 shows the effect on burning of 50 fpm of forced ventilation that is horizontal to the cloth.

Table V

NULL-GRAVITY BURNING RATES OF COTTON CLOTH

Atmospheric Composition	Propagation Rate (in. /sec)		R_{0g}/R_{1g}
	0g	1g	
5.0 psia O_2	***	0.50	--
3.5 psia O_2	0.039	0.46	0.085
3.5 psia O_2 1.5 psia He	0.081	0.44	0.184
3.5 psia O_2 1.5 psia N_2	0.043	0.37	0.116
3.5 psia O_2 3.5 psia He	0.052	0.34	0.153
3.5 psia O_2 3.5 psia N_2	0.046	0.25	0.184

***Not Measurable

It can be seen from Figure 14 that forced convection produces increased burning rates and that the curves of the rates for each diluent-oxygen mixture follow the same trends for free and forced convection in 1g. Forced convection produces an upward shift of the curves, but did not substantially affect the curve shapes.

The burning rate varies with the oxygen partial pressure, as shown in Figure 19. Pure oxygen and air are depicted in Figure 19 because they represented extreme cases for space cabin atmospheres. It can be seen that, as the total pressure increases for a constant atmospheric composition, the burning rate increases accordingly. The slope of the air curve is the same as that for pure oxygen, suggesting that the effect upon the burning rate, of increasing the total pressure of any mixture is equivalent to that of increasing the total pressure of pure oxygen over the same range.

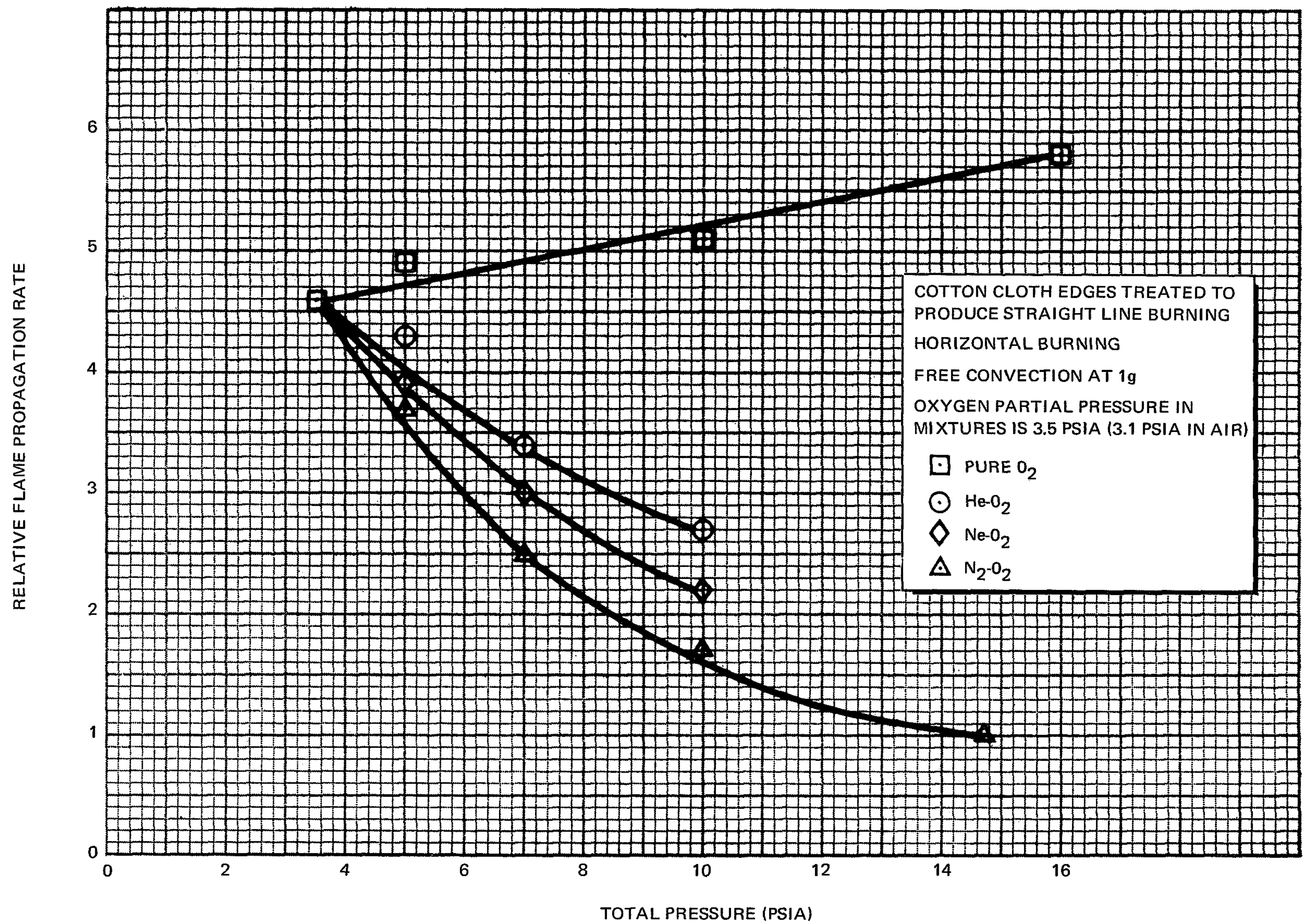


Figure 17. Flame Propagation Rates Relative to Rate in 14.7 psia Air

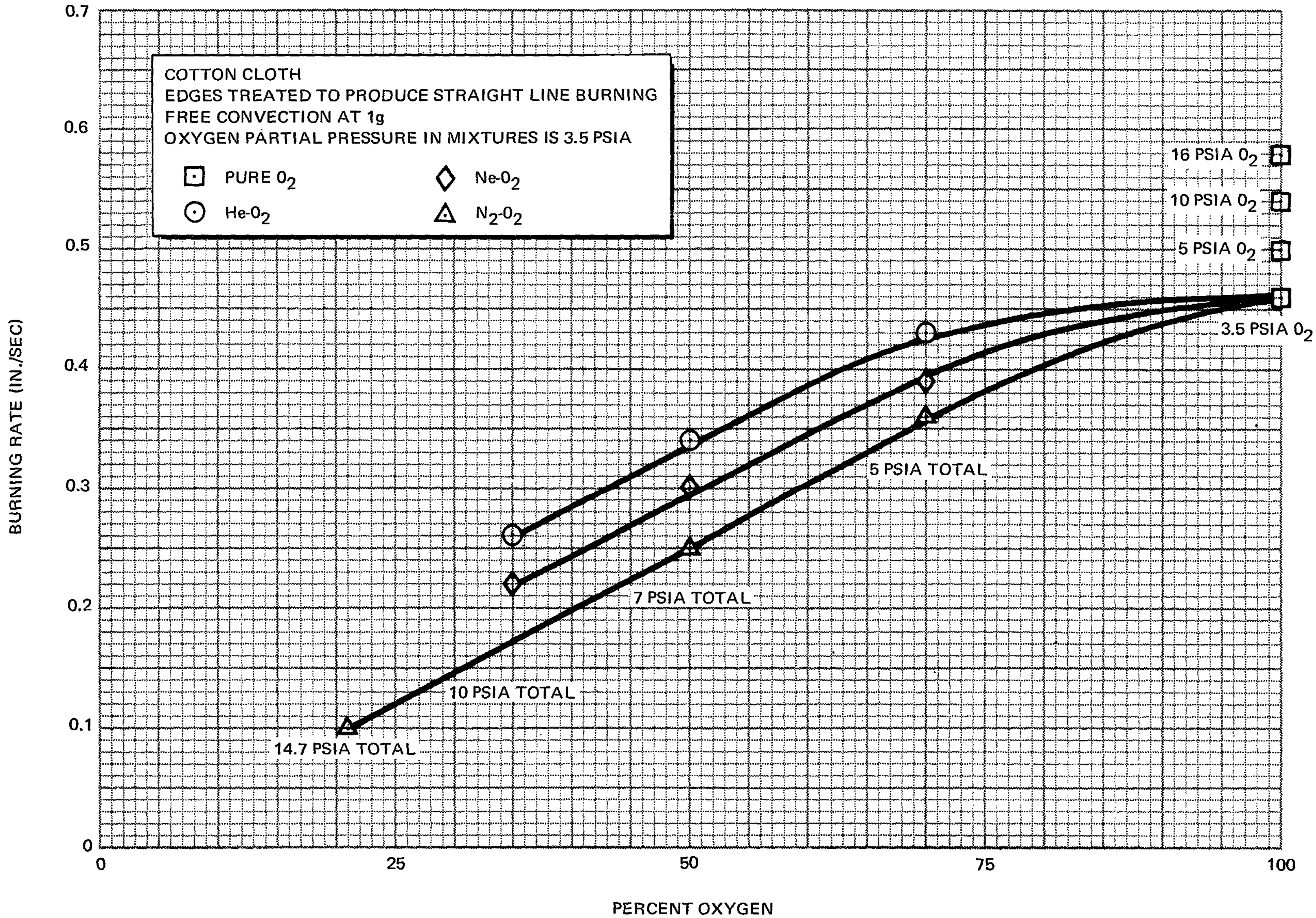


Figure 18. Effect of Increased Diluent Partial Pressure Upon Burning Rate

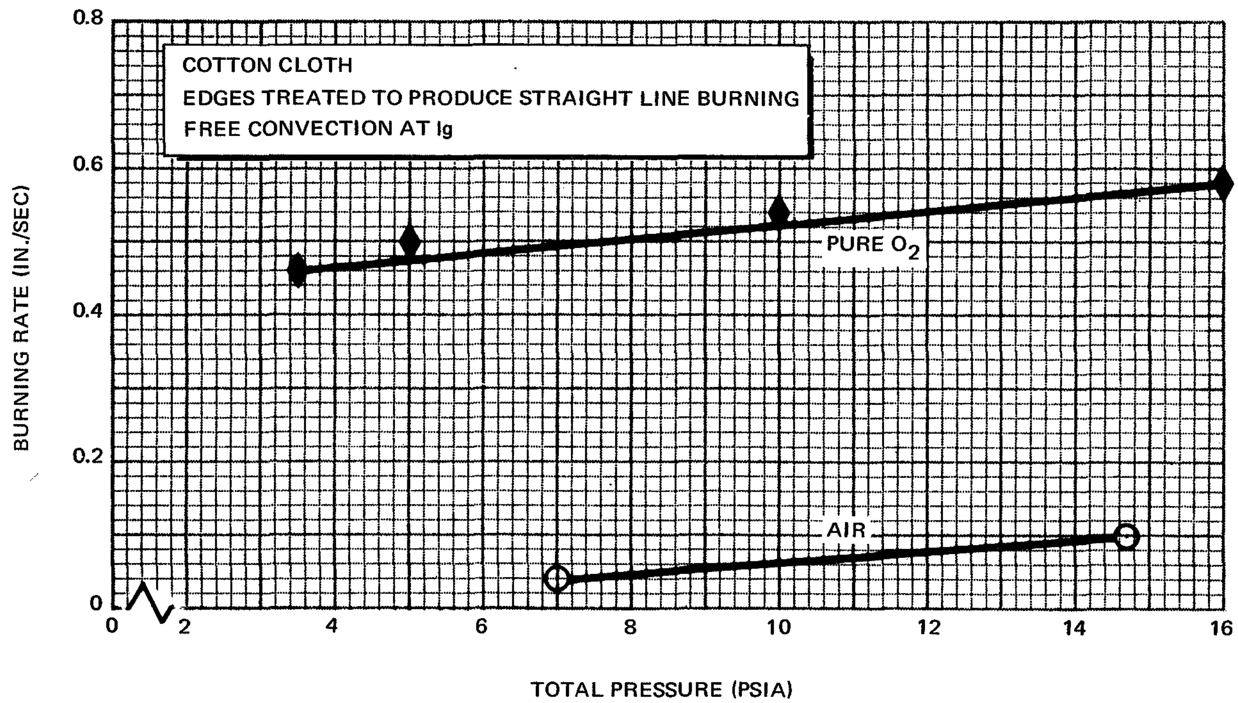


Figure 19. Effect of Increased Pressure upon the Burning Rate

The burning rates are lower when a diluent is added to a pure oxygen atmosphere. This has been attributed to the diluent absorbing heat from the flame that would have otherwise heated more oxygen for the fire. Huggett (ref. 4) suggests a correlation between gas compositions and the flame propagation rates through the molar heat capacities of the gas mixtures. The molar heat capacities of the various atmospheres tested appear in Table VI along with the burning rate and the molar heat capacity with respect to oxygen. The molar heat capacity is defined as the amount of heat that must be added to the gas mixture to heat a mol of oxygen, 1 C^o. An increase in the diluent concentration causes this value to rise, indicating that more heat is needed to sustain burning at the same rate or that the burning rate is decreased when the amount of available heat is fixed. Huggett found that the heat capacity per mole of oxygen was strongly related to the flame spread rate on a surface. The burning rates of the cotton cloth specimens also showed a correlation with the heat capacity of the atmosphere, as shown in Figure 20. The regression on a semi-log graph is similar to that found by Huggett.

It may be noted from TableVI that the new burning rate data for neon-oxygen falls between those of helium-oxygen and nitrogen-oxygen. This result can be expected since neon has a heat capacity equal to that of helium, but a thermal conductivity closer to that of nitrogen. The combined effect can be

Table VI

HEAT CAPACITY OF GAS MIXTURES

Gas Composition	Heat Capacity cal/mole °C	Heat Capacity cal/mole O_2 °C	1-g Flame Propagation Rate, in./sec
3.5 psia,			
100% O_2	7.0	7.0	0.46
5.0 psia,			
100% O_2	7.0	7.0	0.49
70/30 O_2/He	6.4	9.2	0.43
70/30 O_2/Ne	6.4	9.2	0.39
70/30 O_2/N_2	7.0	10.0	0.37
7.0 psia,			
50/50 O_2/He	6.0	12.0	0.35
50/50 O_2/Ne	6.0	12.0	0.30
50/50 O_2/N_2	7.0	14.0	0.25
10.0 psia,			
35/65 O_2/He	5.7	16.2	0.27
35/65 O_2/Ne	5.7	16.2	0.22
35/65 O_2/N_2	7.0	20.0	0.17
14.7 psia,			
AIR	7.0	33.3	0.10

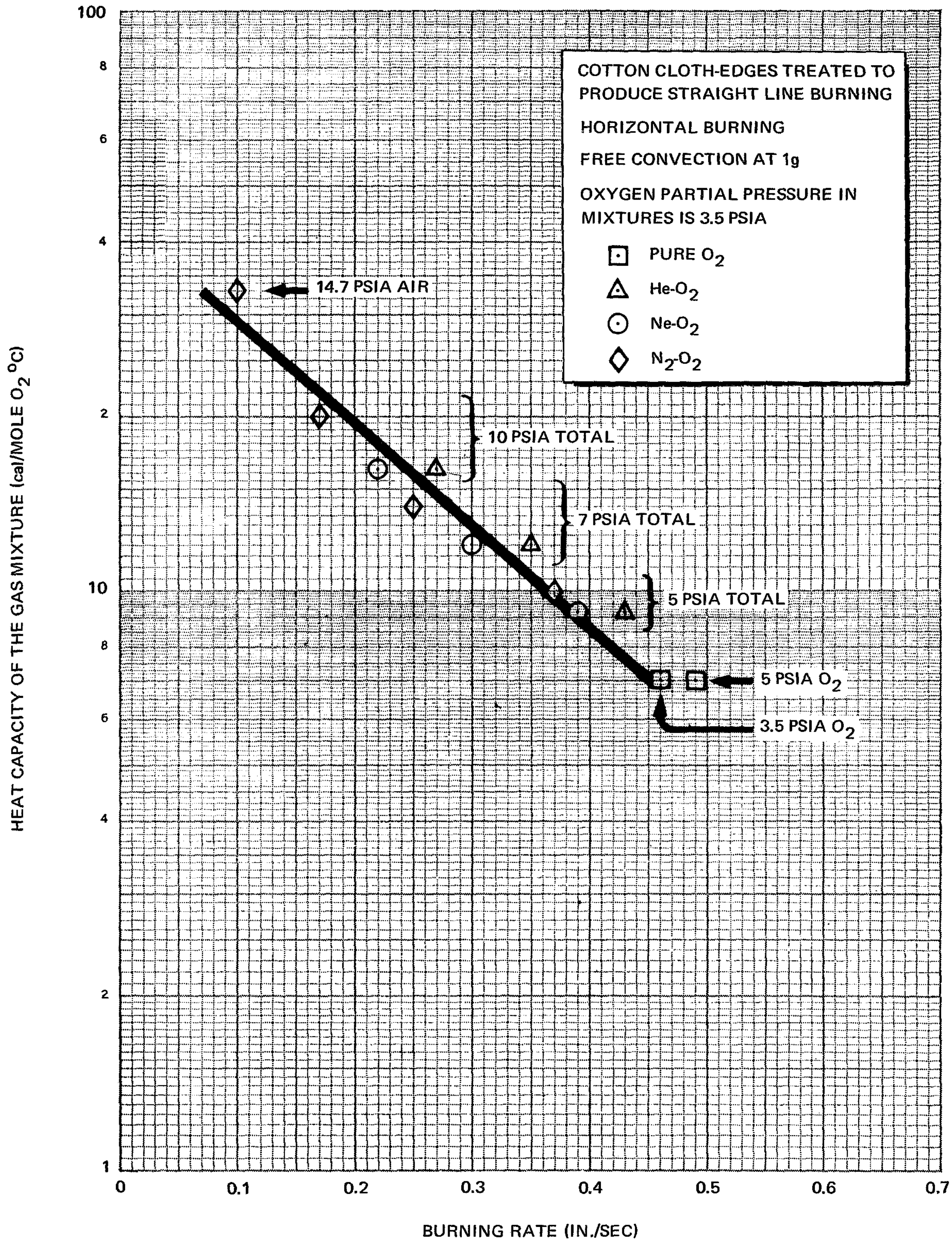


Figure 20. Correlation of Burning Rates in Different Atmospheres

seen in Figure 18, when the burning rate is plotted against percent oxygen in the atmosphere. It can be seen that the first additions of diluent to pure oxygen did little to reduce flame propagation. Not until the diluent concentration was increased to 50% did a sizable reduction in burning rate occur. Tests by Klein (ref. 2) also indicated that the first addition of diluent had only a minor effect on the reaction rate as compared with the burning rate of pure oxygen.

Analysis of Degradation Products of Cotton Cloth

Analysis of the degradation products of cotton cloth confirmed the presence of low molecular weight aldehydes and organic acids as also was reported by Little (ref. 5). The test procedures and apparatus was presented in Section 2. The products, other than H_2O, CO and CO_2, prior to and subsequent to ignition for the cotton cloth specimens are shown below. The compounds listed are those that were found to be present in quantities of 100 ppm or more. There is sufficient amount of these materials to allow rapid response of a suitable fire warning system.

Combustion Products

Pre-Ignition	Post-Ignition
Acetaldehyde	Iso-valeraldehyde
Methyl Ethyl Ketone	Toluene
Acrolein	Isopropyl Alcohol

One potential fire detection concept is a two-wavelength infrared sensor for sensing a generation of hydrocarbons above the normal background level. All combustible organics can be detected by sensing for the carbon-hydrogen bond, on an IR wave-length of 3.45μ, and for the carbon-carbon double bond at 7.0μ. The compounds that have been identified for cotton cloth are suitable for detection by means of a fire sensor. However, because of the various types of materials used aboard a spacecraft, a comprehensive study should be performed on the materials used in each spacecraft during its design period to select a fire sensing and warning system.

Burning of Insulated Wire in Neon Diluent at 1 g

The insulated single wire and a single insulated wire in a bundle were tested and the results described in ref. 1. New data were obtained to evaluate the effect of neon as a diluent as compared to the previously reported helium and nitrogen diluent data. The data from a new batch of the same type insulated wire as that tested and reported in ref. 1 had to be used and varied in most instances in burnthrough time because of a minute difference in thickness. Tests were repeated for the entire spectrum of atmospheric compositions to permit a more exact comparison of the neon data. The burnthrough of the insulation on the single wire with neon diluent nearly falls in between the values for helium and nitrogen diluent, as shown in Figure 21.

It can be seen that the choice of diluent has a significant effect on smoke development and burnthrough on an overloaded electrical wire. The time required for a test wire to begin to smoke and burn through in helium-oxygen atmosphere is considerably greater than in nitrogen-oxygen atmosphere because of helium's higher conductivity. Neon-oxygen times were relative to its thermal conductivity and normally fell between the low conductivity value of nitrogen-oxygen and the high conductivity value of helium-oxygen.

In the presence of 3.5 psia of pure oxygen, the overloaded electrical wire began to smoke and burn almost simultaneously. As the total pressure of the atmospheric mixture increases by adding nitrogen, the time interval between smoking and burnthrough are even more pronounced in helium-oxygen atmospheres. When wires were in bundles, the time to smoke and burnthrough was greater than under all conditions tested with single wires (ref. 1).

Analytical Correlation of Burning Rate Data

Equations were derived to describe the burning rate data of the cotton cloth specimen tested in a horizontal position. The equation (1) used the data from Figures 12 and 13. Equation (2) used the data from Figure 18. Equations (1) and (2) are applied to variations in gravity level and variations in atmospheric composition respectively.

The equations permit the extrapolation of data within 5% or less of actual test values at conditions of 1g or higher. The burning rate in null gravity was assumed to be zero in the derivation of the equation and therefore will disagree in some instances with the actual measurements. Equation (1) represents the second quadrant of an ellipse, and is usable to extrapolate data from a gravity level to another for the same atmospheric composition. The equation is as follows:

$$R = \frac{R_{max}}{G_{max}} \sqrt{2\,GG_{max} - G^2} \qquad (1)$$

where

R = desired propagation rate (in./sec)

R_{max} = the maximum rate (in./sec) measured at g max

G_{max} = the maximum gravity level (g's) to be encountered

G = the gravity level (g's) under consideration

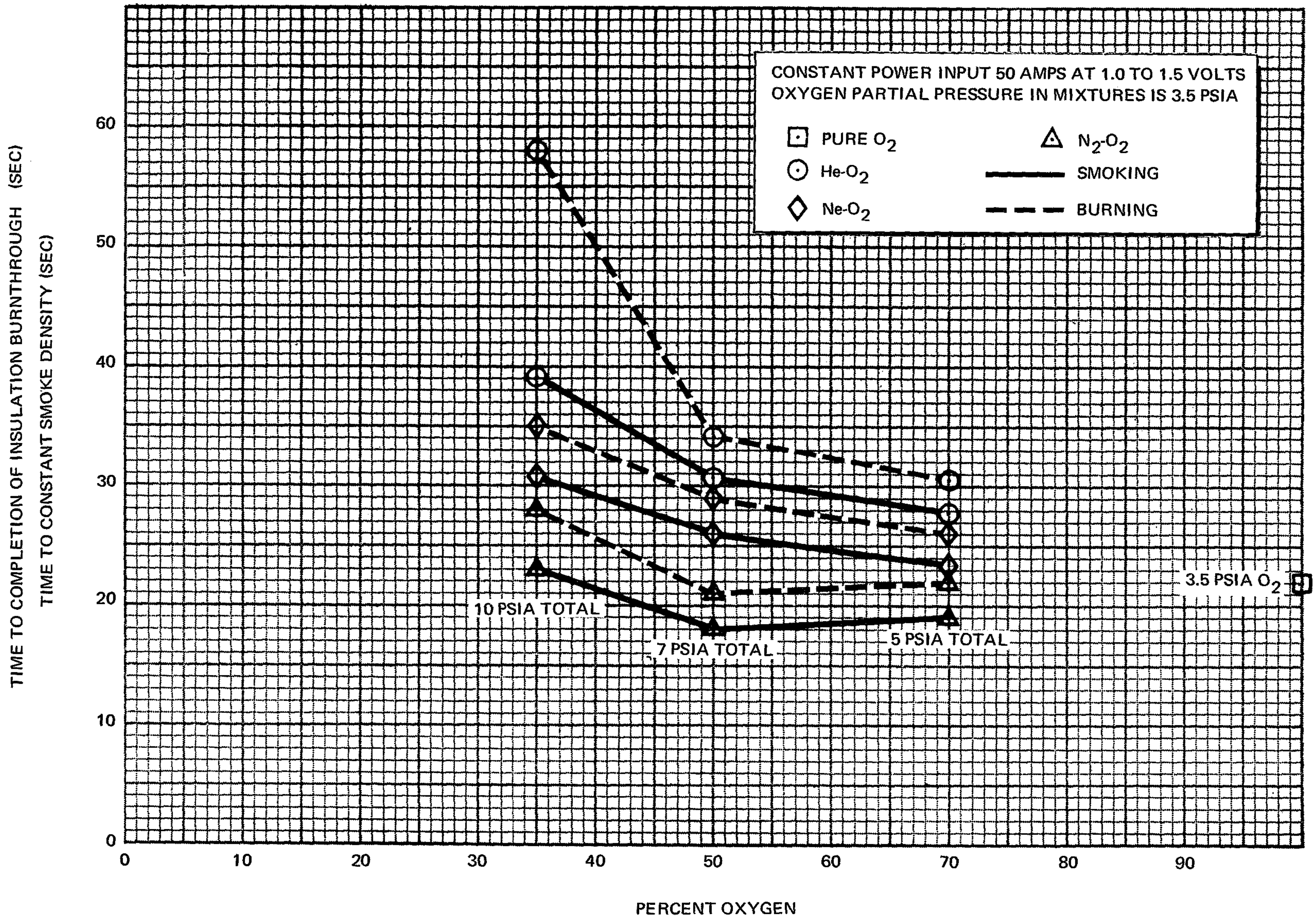


Figure 21. Smoking and Burnthrough of Single Insulated Wire in Different Atmospheres

R_{max} is dependent upon the material being burned, however, it also varies with atmospheric composition and the maximum gravity level of concern. The increase of the burning rate with gravity is less pronounced at elevated-gravity levels, with little change between the 3-g and 5-g values and no significant rate of increase above 5g for the cotton cloth specimen. Therefore, 5g was used for G_{max} and if the 5-g restraint is observed, the R_{max} becomes R_{5g}. This value may be closely approximated if the 1-g rate is known. The relationships of the 5-g rate to the 1-g rate are as follows:

For pure O_2 and N_2-O_2	For He - O_2
$R_{max} = R_{5g} = 1.64\ R_{1g}$	$R_{max} = R_{5g} = 1.44\ R_{1g}$

Equation (1) can be reduced to a more useable form: $R = \delta R_{max}$, where δ is a gravity factor, given in the table below for each g level:

g =	δ =
0	0
1	0.6
2	0.8
3	0.92
4	0.98
5	1.0

Equation (2) describes a downwardly opening parabola, with its center offset from the origin which fitted the curves of Figure 18. This equation can be used to predict, for the horizontal cotton cloth specimen, the effect of atmosphere on burning rate. The expression in equation form is as follows:

$$R = R_{max} - (X - 1)^2 \qquad P_{O_2} = \text{Constant}$$

$$G = \text{Constant} \qquad (2)$$

where

R = desired propagation rate (in./sec)

R_{max} = the maximum rate (in./sec) exhibited in pure O_2

X = the oxygen concentration in the atmosphere as a decimal fraction

The equation correlates closely with experimental data, except when the oxygen concentration was below 0.4; particularly for a helium diluent.

The constraint,

$$X = 0.4$$

was applied to the equation, which was then reduced to a more useable form:

$$R = \sigma R_{max} \qquad P_{O_2} = \text{constant}$$

$$G \cdot \text{Constant}$$

$$X \geq 0.4$$

is tabulated for different oxygen concentrations:

$\%O_2$ =	100	90	80	70	60	50	40	30
X =	1.0	1.0	0.8	0.7	0.6	0.5	0.4	0.3
σ =	0	0.01	0.02	0.09	0.16	0.25	0.36	0.49

The correlation of the calculated data with the test results is good. The average average error was about 2-1/2%. Since the oxygen partial pressure is kept constant and diluent is added to change the oxygen fraction, the equation permits the calculation of values that can be used to compare the effect of diluent upon the burning rate.

It appears possible, from the curve matching previously presented, that equations can be written to extrapolate the burning rate data for different materials tested in 1-g to higher-g conditions. Some test points may be required for the new materials at simulated higher-g levels to augment 1-g data for the atmospheric composition and pressure level of interest. The data are required to develop the equation for a specific material and condition. Forced ventilation rate can be used to simulate the higher-gravity levels. The 1-g 50-fpm forced convection burning rate test data were equivalent to test data obtained on the centrifuge with free convection at about the 1-1/2- to 1-3/4-g level of O_2 and N_2 - O_2 atmospheres and between the 3-g and 4-g level for He-O_2.

Effectiveness of Inert Diluent as a Fire Extinguishing Agent

Several cursory tests were completed to evaluate small amounts of gaseous nitrogen and helium for their ability to extinguish small fires. These gases were evaluated because they are the two most commonly proposed atmospheric diluents. Also, neither of these gases is harmful to the crew as long as acceptable oxygen partial pressure is maintained in the cabin.

A special nozzle was designed and used in the supply of the inert diluent and is shown in Figure 22. The nozzle was necessary to prevent oxygen within

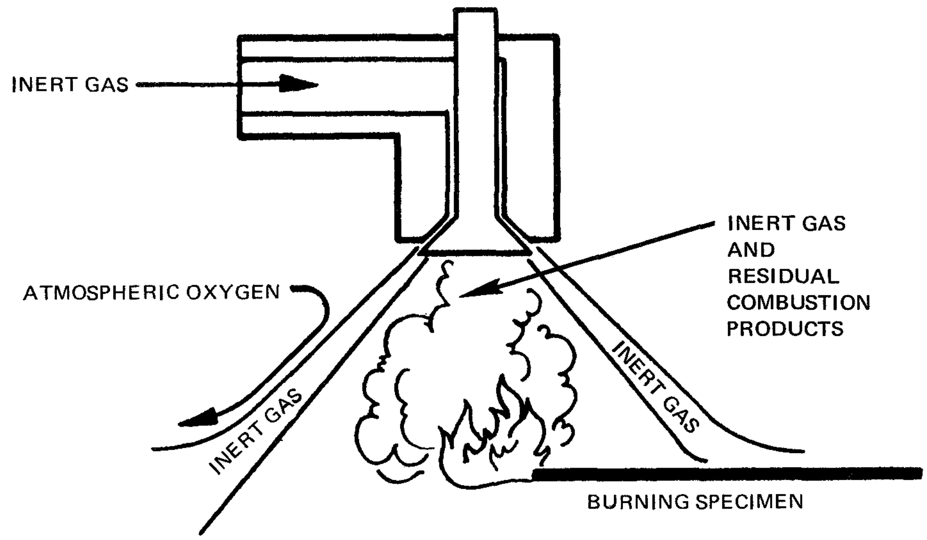


Figure 22. Inert Gas Flooding Nozzle

the bell jar from feeding the fire. The entrained atmospheric oxygen was carried away from the fire, along the outside of the cone, and the burning cloth was blanketed with inert gas and residual combustion products when the cone was centered. A fire was typically extinguished in 2 or 3 sec with the nozzle at a distance of 4 to 6 in. from the cloth.

In nearly every test the specimen smoked after the fire was extinguished. A quenching agent may be required when forced convection is present to augment the gaseous inert diluent spray. Either liquid nitrogen or water could probably serve the purpose. The amount of water exhausted into the atmosphere could be minimized by first putting out the fire with the inert diluent.

It is recommended that further tests be completed on larger specimens than the 16-sq-in. patches of cloth used. Liquid nitrogen and gaseous inert diluent followed by a water quench should be evaluated. If a procedure proves entirely satisfactory, then alternate materials should be evaluated in extinguishing fire tests.

Section 5

CONCLUSIONS

Major conclusions derived from the completed tests and analyses on the effects of atmosphere selection and gravity level on burning rate and ignition phenomena are given in subparagraphs below. Additionally, useful information is also presented on inert diluents for fire putout and pre-ignition combustion products for possible application to fire detection.

(1) The increased free convection created by the higher gravity level significantly accelerated the burning rate of the cotton cloth test specimens until it reached near the 3-g value. In between 3 and 5 g's the burning rate curves began to level out. Above 5 g's the curves began to approach a constant value. The burning rate at 5 g's in nitrogen-oxygen at equivalent pressure levels was about 1.64 times that at 1g. A ratio of 1.44 was obtained for helium-oxygen. The burning rates measured in KC-135 aircraft null-gravity tests were 8% to 18% of test values conducted at 1g for equivalent atmosphere compositions and pressure levels. The measurable burning rates in null-gravity tests varied from 0.039 in./sec to 0.081 in./sec.

(2) Burning rates for zero g were very low because oxygen is only supplied to the flame by diffusion. Tests indicated that a fire extinguished itself in null gravity when no forced convection was present and when the amount of diluent was on the order of that experienced in atmospheric air.

(3) Char front travel on cotton cloth was also very slow in null gravity when no convection was present. With no convection, the gases resulting from a fire accumulated around the char front and formed a spherical flame. The fire decreased in intensity and, in several tests, self-extinguished. Extraneous accelerations created enough momentary convection to cause the mass of gases to burn up. This was most pronounced during the null gravity experiments with pure oxygen.

(4) Data from forced convection tests at 1-g (50 fpm parallel to the cloth) match data taken for equivalent atmospheric composition and pressure levels in the 1.5- to 1.75-g range, without forced convection, for pure oxygen and nitrogen-oxygen atmospheres. A test point using 50 fpm of forced ventilation parallel to the cloth

specimen in null gravity at 3.5-psia pure oxygen matches a 1-g point for the same atmosphere with free convection. Only one of eight data points with forced ventilation in null gravity was usable. It is recommended that further tests be conducted in null gravity with ventilation.

There appears to be little difference from a burning rate standpoint on the selected atmospheric composition for a null-gravity condition if no convection is present. However, the higher convection rates that could be created by the thermal control system or that produced during ground checkout, as well as high-g launch or re-entry conditions, must be considered in the materials and atmospheric selection program. It is recommended that forced ventilation be used to simulate free convection for elevated-g conditions in materials tests. A 75-fpm forced convection rate is a good design value for testing most materials that are considered to be flammable.

(5) New burning rate test data were obtained for neon-oxygen atmospheric mixtures. The neon-oxygen test data for 5 psia, 7 psia, and higher pressure levels fell in between the values for nitrogen-oxygen and helium-oxygen, as would be expected, based on relative thermal conductivity. Neon retarded the ignition more than nitrogen, but less than helium. For example, for 7-psia total pressure with 3.5-psia oxygen, an atmosphere with a nitrogen diluent exhibits a time to ignition for cotton cloth of 6.3 sec. With neon it increases to 6.7, sec, and with helium to 10.2 sec, for a constant power ignition source. The burning rate in a neon diluent atmosphere is less than that for helium, but more than that for nitrogen. For the 7-psia total pressure atmosphere, the 1-g burning rate for cotton cloth with a helium diluent is 0.35 in./sec, for neon, 0.30 in./sec, and for nitrogen, 0.25 in./sec.

(6) The times to smoking and burnthrough of electrically overloaded insulated wire in a neon diluent atmosphere also fell between the values recorded for nitrogen and helium diluent for atmospheres of equivalent pressures. For example, a 7-psia atmosphere with 3.5-psia oxygen and 3.5-psia diluent exhibits a wire burnthrough time of 21 sec for a nitrogen diluent, 29 sec for neon, and 34.5 sec for helium.

(7) The gravity level appeared to have no significant influence upon the ignition temperature, but it did affect the time to ignition. At increased gravity levels, the time to ignition of cotton cloth is generally reduced about 10 to 20%. For example, the ignition time in 5.0-psia oxygen is reduced from 5.5 sec at 1g, to 5.3 sec at 3g, and to 4.3 sec at 5g. This compares to a 5.2-sec ignition time for 50-fpm forced convection in 5 psia O_2 at 1g. Ignition in null gravity is accompanied by a flash, which is attributed to the rapid burning of the combustibles that accumulate around the ignition source in the absence of free or forced convection.

(8) A small fire was extinguished with an inert diluent gas used as the extinguishing agent. Testing in 1g demonstrated that a divergent cone of inert gas prevented oxygen resupply to the fire. The cloth samples smoked after the flame was suppressed. It is recommended that additional tests be completed with a broader range of materials, using inert diluent for putting out small fires. Additionally, a combination of gaseous inert diluent followed by minimal water spray for quenching should be evaluated. In this instance, liquid nitrogen is considered to have a good potential for both suppressing the flame and quenching the fire for absolute put-out.

(9) The cotton cloth test specimens emitted acetaldehyde, methyl ethyl ketone, and acrolein prior to ignition in sufficient quantities (above 100 ppm) to be sensed by fire detection systems. Post-ignition products, i.e., iso-valdraldehyde, toluene, and iso-propyl alcohol are also detectable. The degradation products of each particular spacecraft material must be considered in the design of a rapid fire detection unit.

Other pertinent data are presented below to provide background information. These are abstracted from the first part of the test program reported in ref. 1 and are augmented in many instances with new data.

(10) The ignition temperature of a material is essentially independent of the amount and nature of the atmospheric diluent, but it is dependent upon the oxygen partial pressure and material.

(11) The addition of 1.5-psia nitrogen to 3.5-psia pure oxygen had only a minor effect in reducing the spread of fire. Not until the partial pressure of nitrogen was increased to 3.5 psia did a sizable reduction in the burning rate occur. This agrees with the tests by Klein, which also indicated that the first addition of a diluent had only a minor effect on the reaction rate as compared with the burning rate in pure oxygen.

(12) The tests in 1g indicated that helium diluent retarded ignition better than either nitrogen or neon diluent, but the fire propagated faster in helium diluent after ignition.

Neon diluent data fell in between that for nitrogen and helium diluent for both insulated wire and cotton cloth tests.

(13) Burning times decreased for all of the gas mixtures in 50 fpm forced convection. However, the diluent tended to have a greater relative retarding effect under forced convection than under free convection conditions. This was caused by the diluent carrying heat from the flame front.

(14) The power required to reach the ignition temperature is not significantly higher in ambient sea level air than in pure oxygen atmospheres

at 3.5 and 5 psia. The power input required to reach the same operating temperature is considerably greater using helium as a diluent than when either neon or nitrogen is used. For example, 50% more power is required to ignite cotton cloth samples in a 7-psia total pressure atmosphere containing equal concentrations of helium-oxygen than in nitrogen-oxygen mixtures.

(15) The presence of an inert diluent, once ignition occurred, reduced the flame propagation rate of most of the cotton cloth samples tested at all gravity levels. Nitrogen diluent had a greater effect on reducing the burning rate than either helium or neon with and without forced convection.

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