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QUENCHING AND EXTINGUISHMENT OF BURNING SOLIDS IN OXYGEN-ENRICHED ATMOSPHERES

FINAL REPORT

Contract No.NAS 9-8470

ROBERT L. DURFEE
JACK M. SPURLOCK

Submitted to:

NASA Manned Spacecraft Center
Materials Technology Branch
Houston, Texas 77058
Attention: J. H. Kimzey/ES8

Submitted by:

Atlantic Research Corporation
A Division of The Susquehanna Corporation
Shirley Highway at Edsall Road
Alexandria, Virginia 22314

September 22, 1969

ATLANTIC RESEARCH

A DIVISION OF THE SUSQUEHANNA CORPORATION

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ABSTRACT

An experimental program of two tasks covering two topics in the general field of fire hazards in spacecraft atmospheres was performed. Under Task I, quenching distances for flaming samples of three polymers were determined, as were also quenching parameters for thin polymer films in contact with a heat sink backing. Maximum quenching distances (quenching by a brass foil) observed at oxygen pressures just great enough to allow ignition were about 1/2-inch. Thin films less than about 1/64-inch thick would not propagate flame when protected by a heat sink backing. Under Task II a fire extinguisher was designed and tested which effectively utilized inert gas as an extinguishing agent. Flaming samples of plastic rods and foams were all extinguished within about five seconds under the test conditions used. Nitrogen, argon, and CO_2 produced similar results as extinguishing agents for foam samples with the CO_2 producing the shortest extinguishment time of 2.3 sec.

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1.0 INTRODUCTION

The program of research under Contract NAS9-8470 was conducted in two separate tasks, both of which relate to the general problem of protection against the hazards of fires in oxygen-rich spacecraft atmospheres. Task I of the program consisted of experimental research into the quenching of burning solids by metal surfaces and other shapes, somewhat similar in nature to the quenching of gas flames by small-diameter holes (as in flame arrestors) or other solid surfaces. The objective of Task II of this program was to perform feasibility testing on a prototype of a compact, inert-gas fire extinguisher which might prove to be of value in a pure oxygen environment.

2.0 TASK I - QUENCHING STUDIES WITH BURNING SOLIDS

2.1 PURPOSE OF TASK I

For flames of premixed gases the principles underlying quenching by closely spaced heat sinks have been developed. The quenching distances for such mixtures are uniquely determined by the mixture stoichiometry and the total pressure. Generally the quenching distances for gases are quite small; for example on the order of 0.008 in. for a stoichiometric mixture of oxygen and propane at one atmosphere. For such gases the quenching distance is roughly inversely proportional to the system pressure.

Quenching by heat sinks is not clearly defined in heterogeneous fuel-oxidizer systems. However, quenching of a flame on solid fuel in air or oxygen can be achieved by close proximity of a heat sink, and the quenching distances are believed to be at least an order of magnitude greater than those for premixed gases. For instance, a horizontal slab of acrylic plastic burning in pure oxygen can be extinguished by the presence of a metallic heat sink about 0.75 inches above the flame, so long as the total pressure is less than 55 mm Hg. In the absence of the heat sink, combustion continues as oxygen pressure is reduced until a value of about 10 mm Hg is reached.

Determination of quenching distance data for materials selected for use in spacecraft, and definition of the effects of total pressure and oxygen concentration upon quenching distances, may prove very important to future spacecraft design. If combustibles are located proximate to a heat sink, then a fire could ostensibly be extinguished simply by partial venting of the cabin without resort to an inert gas purge or the use of chemical suppressants. Under more favorable conditions of atmospheric composition such a fire might be prevented through application of quenching distance data in system design.

2.1.1 Quenching of Gas Flames by Solid Surfaces

A substantial portion of the work on quenching of flames by solid surfaces was surveyed by Wohl[1]. Date on quenching distances (parallel plates) and quenching diameters (round tubes) can be found for many gaseous mixtures of hydrocarbons with oxygen and air in reference 2. These data were obtained as the maximum distances (or diameters) between (or within) which flame will not propagate from a spark discharge; thus, the values may not be directly applicable to the quenching of an established flame.

Quenching distance data have been correlated reasonably well on a heat transfer basis and also on the basis of destruction of chain (reaction) carrier species on the wall[3]. Minchin[4] has suggested that, based on his results with coal gas/air mixtures, some of the heat loss from a flame in a plate perforation was due to radiative loss. In addition, Holm[5,6] concluded from his work with various materials and perforation geometries that quenching was due to cooling of the flame front by heat conduction into the unburned gas, and not by conduction to solid surfaces.

These various interpretations by reputable workers in the field reveal the complex nature of the quenching phenomenon in gases. No definitive mechanistic model has been developed thus far, and even the best correlations of quenching distances with temperature, pressure, stoichiometry, and geometry are somewhat limited in accuracy and range flexibility.

2.1.2 Heterogeneous Flames

Quenching of a heterogeneous flame could prove to be simpler or more complex analytically than quenching of gas flames. One factor believed important in gas flame quenching, the destruction of chain carriers or other species on solid surfaces, may not enter significantly into quenching of a burning solid. On the other hand, the mechanism of heat feedback onto the unburned solid may be more difficult to express analytically than the strongly diffusive feedback present in gases. Berlad and Potter[7] found that small cold surfaces immersed in gas flames produced large quenching effects, especially when the cold surface was a solid rod concentric within the tubes used to determine quenching diameters. This result may indicate a high order of sensitivity of flames on solids to the temperature and geometry of the heat sink used to quench them.

2.2 EXPERIMENTAL APPARATUS AND MATERIALS

The experimental test chamber used for all of the tests in Task I was a 3 ft. x 1.5 ft. x 1.5 ft. box constructed of 1/2 inch thick aluminum plates welded together. This chamber was outfitted with sufficient access ports, including a Plexiglas viewing port, power inputs, and remote manipulators which enter the chamber through Teflon gaskets. The remote manipulators allowed the operator to position the heat sink, the sample, and the hot-wire igniter during a test. The test chamber was evacuated to 0.1 mm Hg by means of a vacuum pump prior to admission of 99.5 per cent pure (USP) oxygen gas. Oxygen pressures were chosen in advance, and were set by means of a manometer. Gas mixtures of known composition were obtained by adding required partial pressures of each component according to the manometer.

The experimental assembly within the chamber as depicted in Figure 1 was used for all Task I experimentation, except that in the studies utilizing quenching by the aluminum support plate only the probe rod and quenching foil were not present. The general test procedure was to position the sample in contact with the face of the aluminum plate with from 0.5 inch to one inch of the sample extending beyond the plate to provide good ignition. Then the quenching foil (if used) was positioned perpendicular to the sample extending beyond the plate to provide good ignition. Then the quenching foil (if used) was positioned perpendicular to the sample and about one inch from the edge of the plate. Normal sample length was 3 inches. In a few tests with rod-shaped samples the sample was held a set distance from the aluminum support plate by another positioning arm and clamp. After positioning was set the desired atmosphere in the chamber was obtained, and then the igniter was switched on and touched to the sample. The igniter was held against the free end of the sample until representative burning had been established over

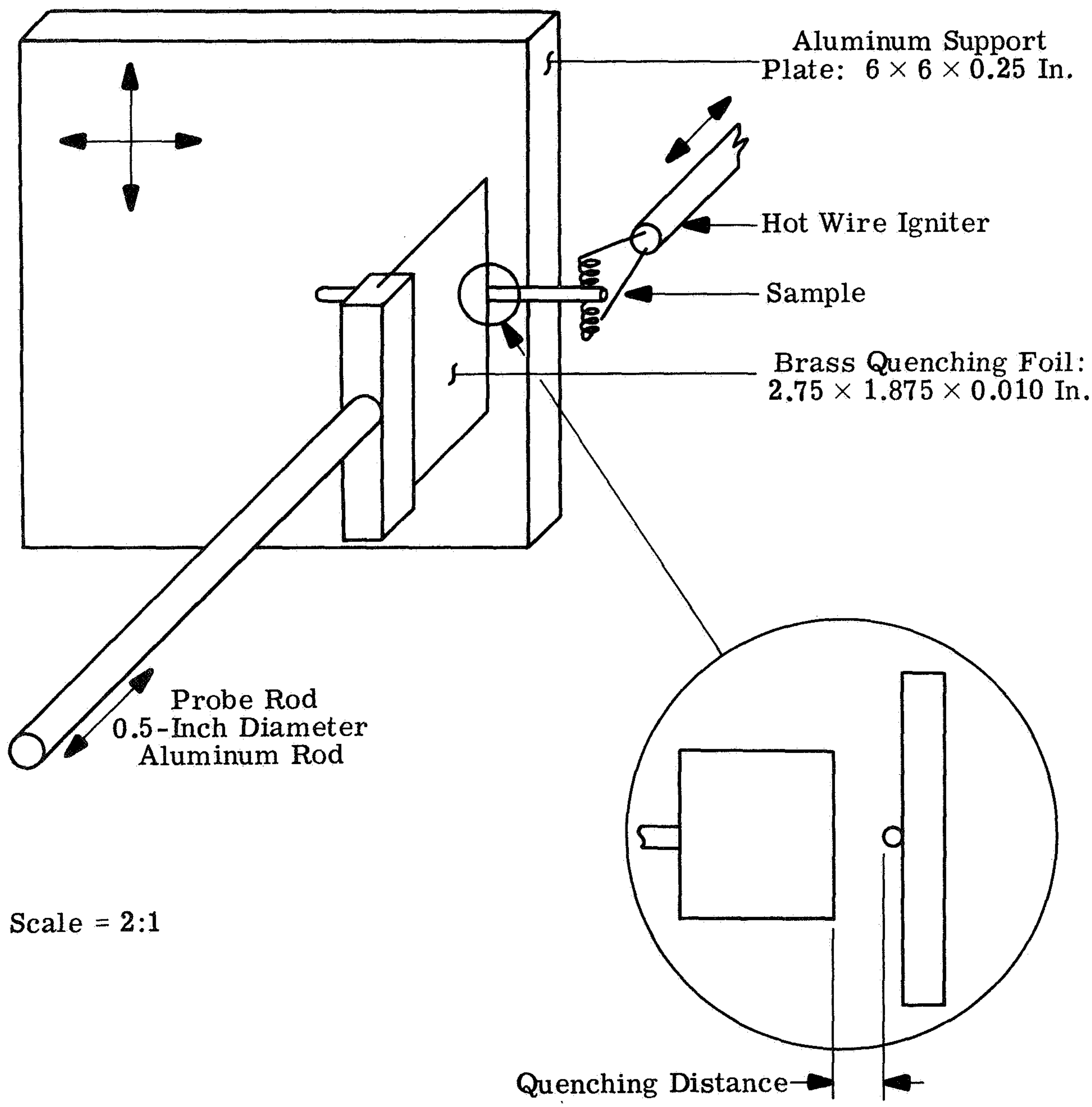

Figure 1. Sketch of Test Setup.

over the entire free end of the sample. Motion pictures were obtained of some tests in order to study the flame action before and during quenching.

Three materials were studied - polycarbonate, nylon and polyacrylic. The molecular weights were not obtained. Sample shapes included 1/8-inch diameter rods, 1/8-inch thick flat sheets, and films of varying thickness. Some of the thinner films were cast from a solution of the polymer into a flat-bottom glass container. Thicknesses of these films as determined by a micrometer were found to vary only slightly across the entire cast surface. In the tests with films a broad face of the sample was caused to adhere tightly to the aluminum plate through the application of a very small amount of adhesive spread over the entire sample face.

The pressures reported herein at which quenching occurred were determined by varying the chamber pressure by steps of 5 mm Hg (or less, in some cases). The highest pressure at which quenching occurred three times out of three tests was taken as the pressure corresponding to a set quenching distance. In most of the tests the results were very reproducible; only in a few instances did quenching occur in only two out of three or one out of two tests for a given pressure. At lower pressures than those reported quenching was always noted.

2.3 EXPERIMENTAL RESULTS

2.3.1 Preliminary Experiments - Quenching with Support Plate Only

Extinguishment of the flame on burning 1/8-inch-diameter rods and 1/8-inch-thick flat strips of various plastic materials was found to occur as the result of contact between the burning rod and a massive heat sink (the aluminum support plate in Figure 1), but the highest pressures of pure oxygen at which this effect was produced were only slightly higher than those at which ignition of the rod could not be obtained (hot wire ignition - 50 watts total energy). For instance, polycarbonate rod could not be ignited in 20 mm Hg pure oxygen. In 30 or 35 mm Hg pure oxygen the rod could be ignited but would not burn past a massive block of aluminum in lateral contact with the rod, and at 40 mm Hg the entire length of the rod would burn even though there was contact with the block. Under no conditions could extinguishment be obtained (short of the no-ignition case) when the heat sink was 1/16-in or further from the surface of the rods.

Similar results were obtained with polyacrylic rods in that the no-ignition O_2 pressure was 10 mm Hg, and burning past the aluminum block occurred at less than 20 mm Hg oxygen. Smaller heat sinks, consisting of 3/4-inch-thick copper discs about two inches in diameter, exhibited essentially the same type of effect. Results of these tests are shown in Table I. Addition of nitrogen to the oxygen did not have as strong an effect as changing the geometry of the samples to 1/8-inch thick flat strips.

2.3.2 Quenching by Metal Foil

Since the single heat-sink method of extinguishment did not appear to produce useful results with 1/8-inch rods at pressures above about 40 mm Hg, we modified our approach to more closely simulate the "enclosed" geometry used in flame-quenching of gas mixtures. The geometry we chose was a burning rod in contact with a flat plate (heat sink), which in a gross manner simulates an insulated wire across a surface. The burning rod is approached by a thin plate (10 mil foil) of brass so that the edge of the foil was a known distance from the rod. The foil edge was parallel to the plane of the surface of the flat plate and was perpendicular to the center line of the horizontal plastic rod, as shown in Figure 1.

Data collected with polyacrylic, nylon, and polycarbonate rods are presented on Figure 2. The "distance between rod surface and the edge of the copper sheet" was determined from each series of "go-no go" tests as halfway between the distance of approach where flame continuation occurred and the distance of approach where extinguishment occurred. Steps of 1/32-inch were used in each test series, so that the abscissa values are always in sixty-fourths of an inch.

The data on Figure 2 follow very regular patterns, with the position of the plots determined by the type of material. Of the three plastics used, polyacrylic was the most easily ignited, burned most rapidly, and exhibited lower quenching distances at a given pressure than the other two. Nylon

TABLE I

Quenching by Contact Heat Sink of Plastic Samples

Test Conditions	Maximum Total Pressure at Which Quenching Occurred (mm Hg)		
	Nylon	Polycarbonate	Polyacrylic
1/8-in. Rods in 99+% Oxygen	40	35	15
1/8-in. Rods in 70% O_2, 30% N_2	50	70	20
1/8-in. Wide Flat Strips in 99+% O_2*	75	170	50

Pressure of 99+% Oxygen at which 1/8-in. Rods would not Ignite (mm Hg)	
Polycarbonate	Polyacrylic
20	10

*Edges protected against combustion

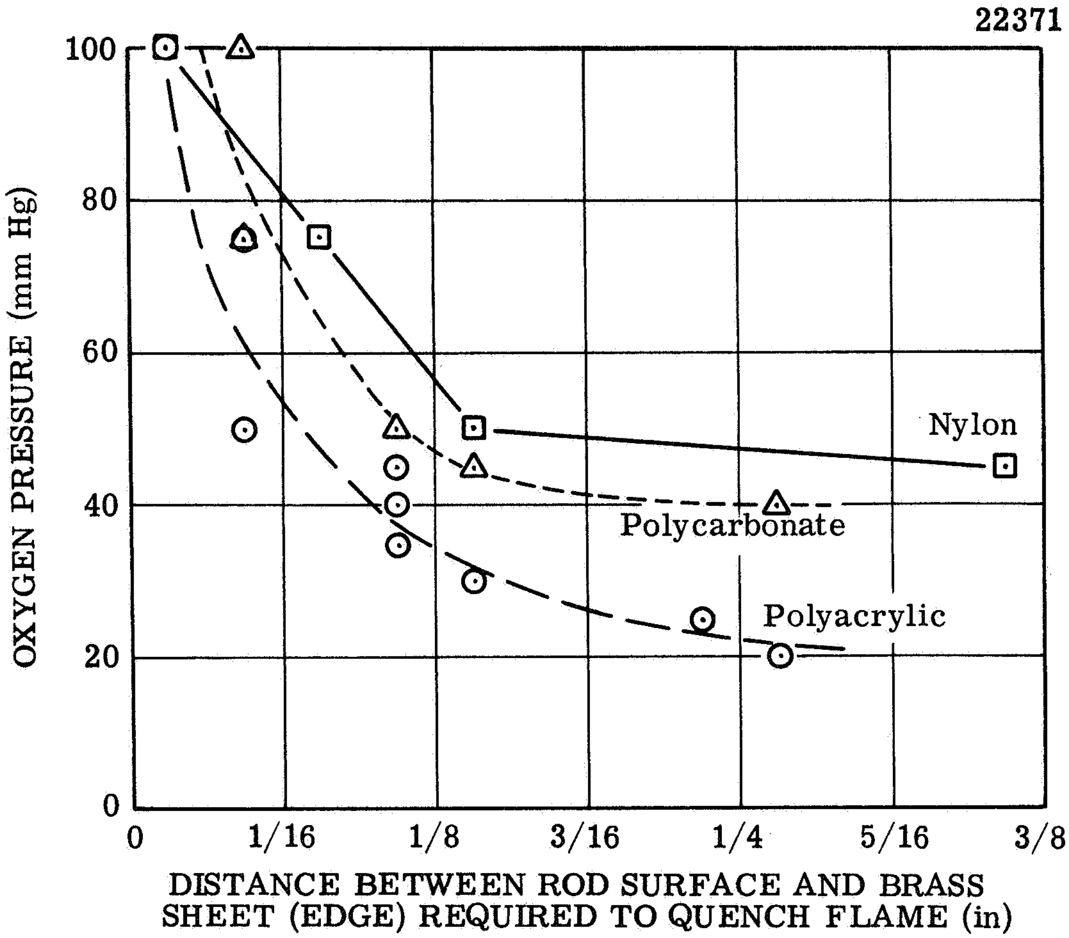

Figure 2. Quenching Distances for 1/8-Inch Plastic Rods in Pure Oxygen. (Rods in Contact with Massive Aluminum Plate - Quenching by Thin Brass Sheet).

burns the slowest of the three and exhibited the largest values of quenching distance at a given pressure. Quenching with the foil began at pure oxygen pressures in the range of 100 mm Hg, although the distances at 100 mm Hg are probably not really quenching distances since melting and enlargement of the rod due to the burning caused contact between rod and foil. This did not occur in the tests at 75 mm Hg pressure.

The effect of diluting the oxygen with nitrogen upon the quenching by a brass foil of burning 1/8-inch diameter rods is shown in Figure 3. The major difference between the plots for pure oxygen on Figure 2 and for 70 per cent oxygen, 30 per cent nitrogen on Figure 3 is that quenching began at higher pressures in the mixed gas. The largest quenching distances were again on the order of 3/8-inch at relatively low pressures. If 3/16-inch is taken as a significant and potentially useful quenching distance, then the corresponding pressures for quenching in pure oxygen are all below 50 mm Hg; for 70 per cent oxygen, 30 per cent nitrogen, the corresponding pressures are below 100 mm Hg.

Other tests of quenching by the metal foil were performed with flat strips (1/8-in. x 1/8-in. x 3 in. long) of the three polymeric materials. Results from these tasks are compared with data from 1/8-inch diameter rods on Figure 4. All of these flat strips were protected on three sides (on the rear by the aluminum support, on the top and bottom by high-temperature cement), and this protection is reflected in the relatively large differences in quenching distance versus pure oxygen pressure compared to the unprotected rods.

2.3.3 Quenching of Burning Films by Heat Sink Backing

Strips of various thicknesses of films made from the three polymer materials were attached to the aluminum support with a small amount of glue (made from polyacrylic dissolved in trichloroethylene) and ignited. The pressures of pure oxygen at which the flaming films would be quenching at the edge of the support plate were determined as described previously.

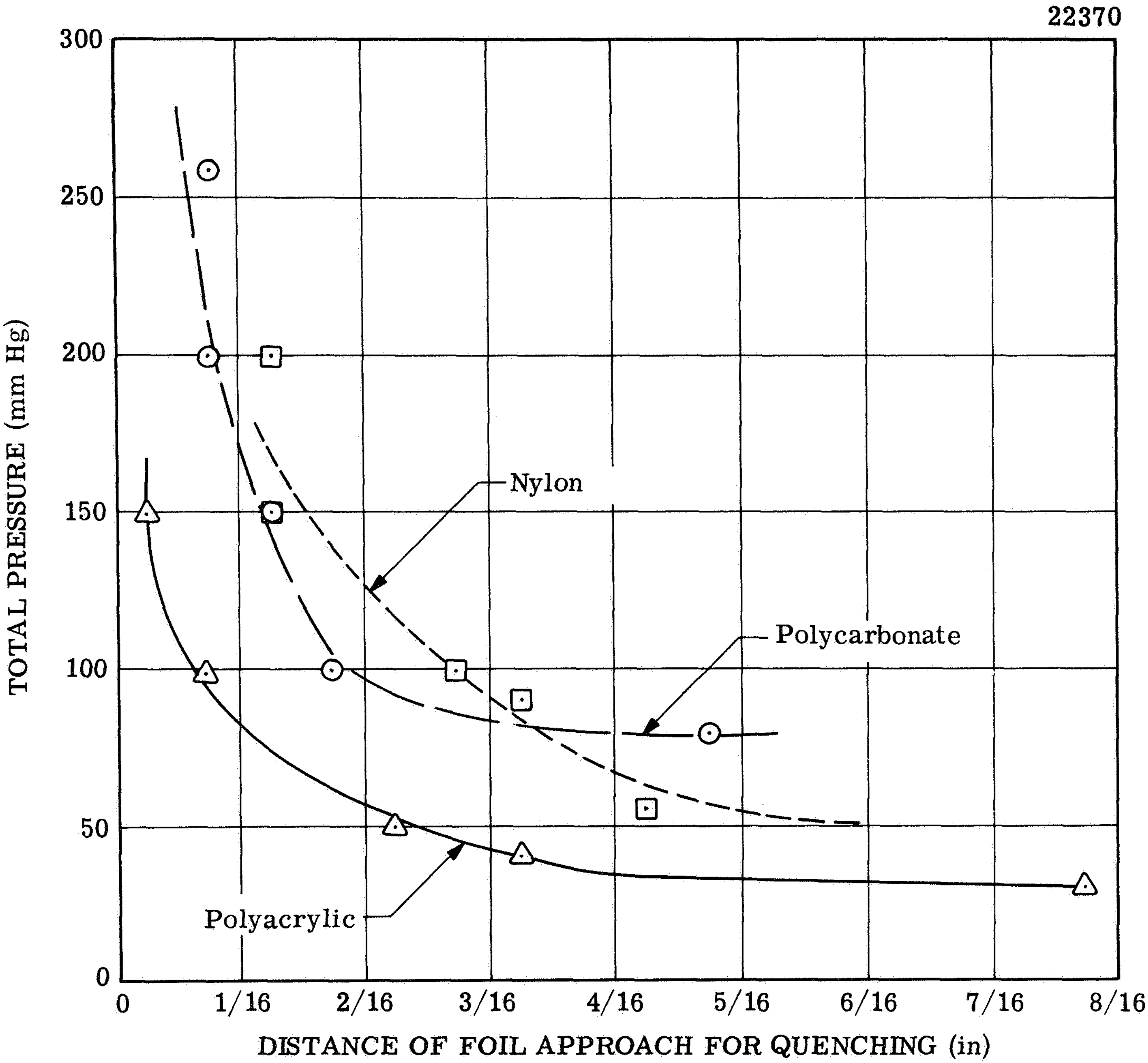

Figure 3. Plot of Total Pressure Versus Quenching Distance by Brass Foil of 1/8-Inch. Diameter Rods in Contact with an Aluminum Plate - (Atmospheric Composition 70 Percent Oxygen, 30 Percent Nitrogen).

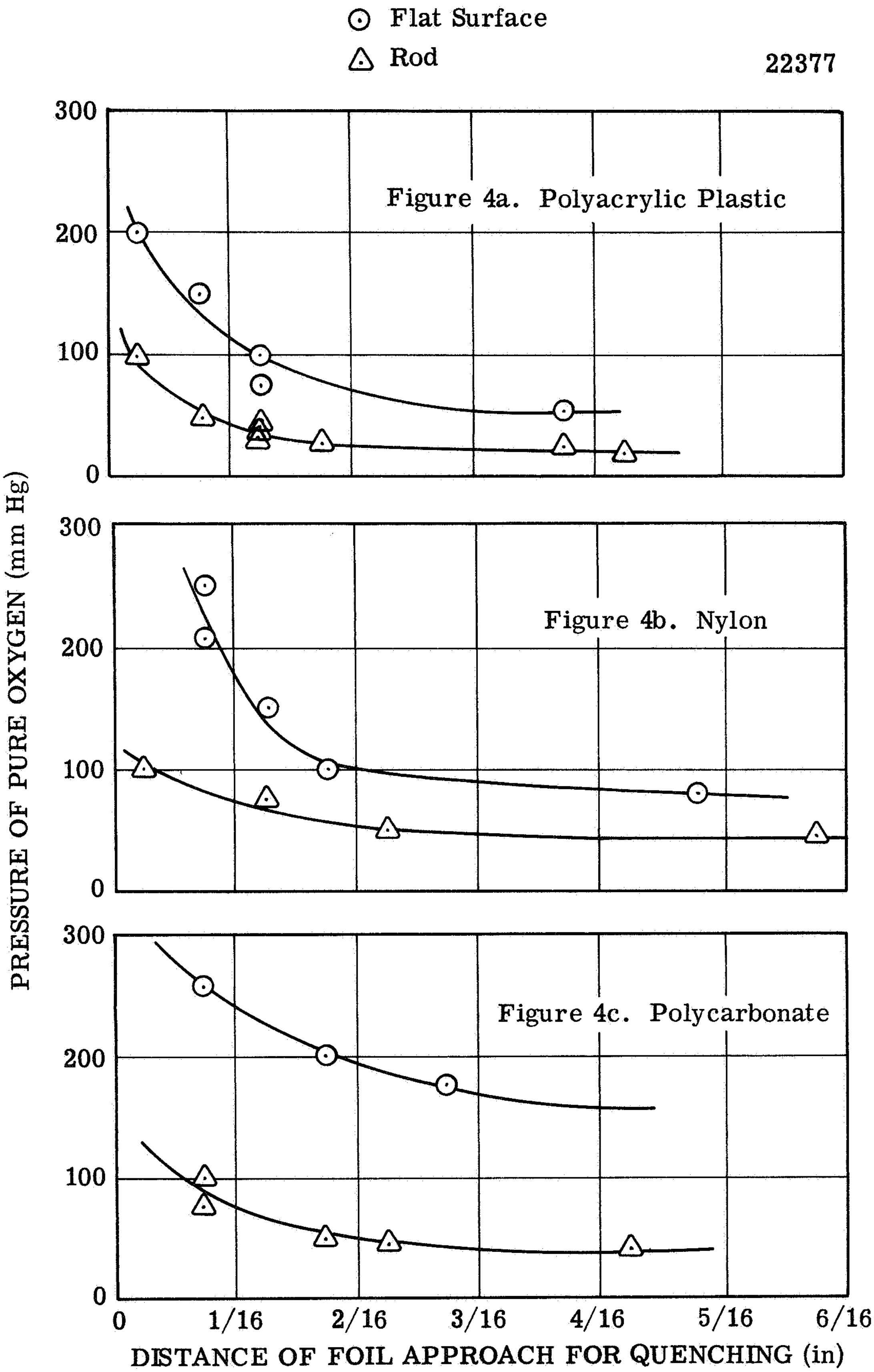

Figure 4. Comparison of Quenching Distances from Tests of 1/8-Inch Rods and 1/8-Inch Flat Surfaces for Three Plastics.

The results of these tests are presented in Figure 5 and Table II. The data in Table II are for those tests with very thin films from which no maximum oxygen pressures were obtained (i.e., only selected levels of pressure were used; step increments were not employed). The data in Figure 5 and Table II indicate that there is a relatively weak dependence of maximum pure oxygen pressure for quenching upon sample thickness at thicknesses above 1/64-inch. Below this thickness, however, there is a very strong dependence of "quenching pressure" on film thickness. Nylon and polycarbonate films below about 12 mils (0.012 in.) in thickness will not propagate flame across a heat sink backing (to which the film tightly adheres over its entire area) at a pure oxygen pressure of 258 mm Hg. For polyacrylic, the critical thickness for flame propagation across a heat sink surface at 258 mm Hg pure oxygen is between 4 and 8 mils.

The low pressure values for nylon films at about 16 and 32 mils were reproduced in separate tests. However, no explanation for the unusual behavior of nylon on Figure 5 compared to the other two polymers is available.

The two tests with the one-inch wide samples of polyacrylic in Table II indicated that there would not be a significant effect of film width on the quenching process. This was studied with a 15-mil nylon film, and the test results are presented in Table III. These data do indicate that there is no effect of film width on the observed quenching.

2.4 DISCUSSION OF QUENCHING RESULTS

One of the most interesting aspects of the quenching studies has been the reproducibility of the oxygen pressures at which quenching occurred. This was observed both for quenching with heat sink backing only and for quenching with heat sink backing plus a metal foil held perpendicular to and at various distances from the samples.

Both types of quenching were found to be strong functions of material type and geometry, but the largest changes in oxygen pressures

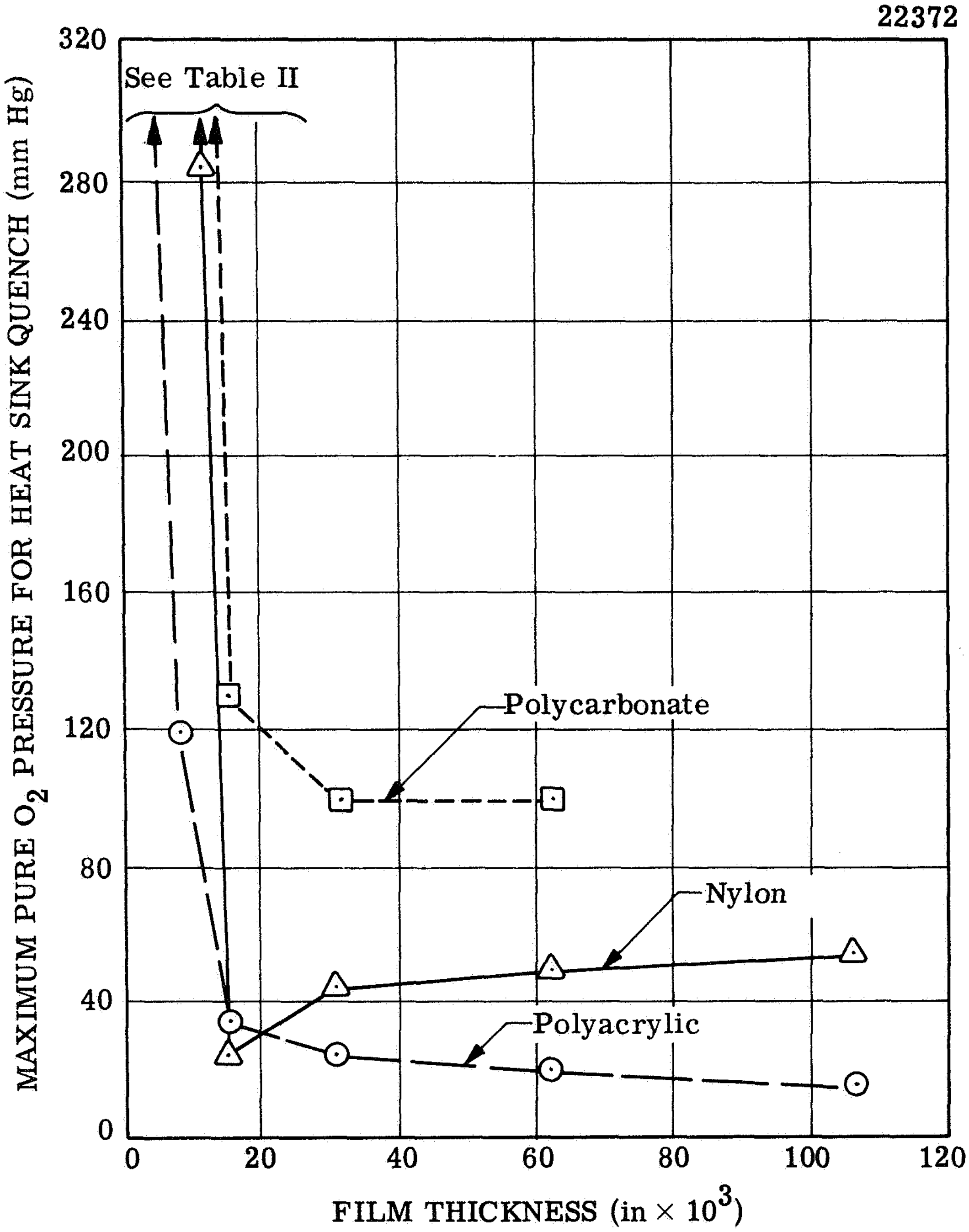

Figure 5. Effect of Film Thickness on Maximum Oxygen Pressure for Flame Quenching by Heat Sink Backing. All Points Based on at Least Three No-Burn Samples.

TABLE II

Results of Flame Propagation Tests for Thin Films of Three Polymeric Materials Across a Heat Sink Surface
(Data from Single-Sample Tests)

Material	Film Thickness (in)	Pressure O_2 (mm Hg)	Sample Width (in)	Did Flame propagate Past Heat Sink Edge
Polyacrylic	4.0×10^{-3}	258	0.25	No
Polyacrylic	4.0×10^{-3}	516	0.25	No
Polyacrylic	4.5×10^{-3}	258	1.0	No*
Nylon	12.0×10^{-3}	516	0.25	Yes
Nylon	5.5×10^{-3}	258	0.25	No
Polycarbonate	5.5×10^{-3}	258	0.25	No
Polycarbonate	5.5×10^{-3}	516	0.25	No

*Two tests

TABLE III

Effect of Film Width on Quenching of Burning 15 mil Nylon Film by an Aluminum Heat Sink Surface (Data from Single-Sample Tests)

Pressure of Pure O_2 (mm Hg)	Sample Width (in)	Did Flame Propagate Past Heat Sink Edge?
30	1.5	No
30	2.0	No*
30	4.0	No*
40	1.5	No*
40	1.5	Yes
40	2.0	Yes
50	4.0	Yes

*Burned slightly (less than 0.5 in.) past heat sink edge at which quenching occurred were caused by addition of the brass foil near the samples. For rod samples placement of the brass foil 1/32-in from the sample surface increased the maximum oxygen pressure for quenching by a factor of about five, and for flat strip samples (with protected sides) this factor was about four for nylon and polyacrylic and about two for polycarbonate. However, it appears from Table I and Figure 4 that sample geometry was much more important for polycarbonate than for the other two polymers.

The results obtained and the points discussed in the preceding paragraph indicate the complexity of the quenching process. Obviously the heat sink capability of the backing material and the material type are both very important. For quenching by the foil it appears that the heat sink capability of the foil is not important. This statement is based on the observation that many of the samples burned slightly past the foil edge before being quenched. This suggests that blockage of convection currents by the aluminum plate and by the foil contributes strongly to the quenching by preventing or hindering the removal of combustion products. If this is the case, then larger quenching distances of the type reported here may be available under reduced gravity conditions.

An interesting observation was made during the tests with nylon samples. During combustion the sample was surrounded by two "halos" of light; one was bright and very near the sample, and the other was faint and appeared further from the sample as the oxygen pressure was decreased. Quenching of the burning nylon occurred whenever the outer (faint) halo came into contact with the foil.

The longest quenching distances obtained with the foil were on the order of 1/2-inch, and these were obtained at total pressures approaching the pressures at which ignition would not occur in the particular atmosphere used. Thus, it appears that the particular quenching used here would not present significant protection against fire-spread in pure oxygen, even under partial venting conditions where pressures might reach 100 mm Hg. However, other geometries might prove somewhat useful; these could include plastic shapes between horizontal plates, rods in tubes, and others.

The results obtained with thin films backed by a heat sink surface indicate that many types of polymer films and paints could be used in spacecraft atmospheres, including 258 mm Hg pure oxygen, so long as their thickness is kept below about 0.010 inch. The "knee" in the plots on Figure 5 indicates that it is at a thickness of about 0.01 inch for which heat transfer to the backing plate becomes great enough to offset heat transfer from the burning surface to the unburned portion of the film. It would not be expected that the results obtained with the thin films would be greatly altered by a reduction in gravitational field, since the quenching is believed to depend on competition between conductive heat transfer processes and not on convective processes.

3.0 TASK II - FEASIBILITY TESTS OF PORTABLE FIRE EXTINGUISHER

For future space missions it appears likely that a distinction between types of onboard fires could be made on the basis of fire size and location. For instance, a large fire or one which affects critical system components should be extinguished using all available means. This type of fire will probably cause abortion of the mission, as a result of the fire effects and/or the extinguishment method. For the large or critical fire an extinguishment method of maximum effectiveness (such as a low-density foam system) would be necessary.

There is also the possibility of relatively small sized onboard fires which, once extinguished, would probably not result in abortion of the mission. For these types of fires it appears more attractive to use an extinguishment method which would be less disruptive to mission activities than the foam system. One type of extinguisher which should serve this purpose is a hand-held unit which can both isolate the small flames and extinguish them with a gaseous agent. The objective of Task II was to demonstrate the feasibility of a particular extinguisher design conceived during the course of the program. An idealized fuel geometry consisting of a flat-plate surface was used in the feasibility tests.

3.1 EXTINGUISHER DESIGN CONSIDERATIONS

The primary considerations for design of an effective inert-gas fire extinguisher (for small fires) to be used in a pure oxygen atmosphere under zero "g" conditions are listed as follows:

(1) The fire must be isolated, preferably by a combination of extinguisher geometry and a curtain of inert gas;

(2) Oxygen present in the vicinity of the fire must be removed rapidly and replaced by inert gas;

(3) Provision must be made to prevent spread of fire-brands (burning fragments of material).

These considerations were incorporated into a conceptual design with the following features:

(1) The conceptual extinguisher design is a truncated cone (dimensions to be optimized) with a gas-carrying circular tube surrounding the end to be directed at the fire (base of the cone) and the other end open (restricted opening);

(2) The circular tube at the base includes a continuous slot at the bottom to provide a curtain of inert gas, and orifices 30° from the slot directing inert gas jets towards the fire;

(3) The restricted opening at the top allows the oxygen near the fire to be swept upward and out of the extinguisher (chimney effect), and a fine screen over this opening would prevent escape of fire-brands.

A sketch of this conceptual design is presented as Figure 6. The cone portion could be constructed of overlapping sections designed to "telescope" into the full length, so that the storage space could be made small. The design on Figure 6 should be considered conceptual only. It should not be considered that this is an optimized design nor that it can apply to all types of 'small' fires due to possible interfering structure or the lack of a flat-surface geometry.

3.2 PROTOTYPE EXTINGUISHER FOR FEASIBILITY TESTING

It appeared beyond the program scope to construct a prototype of the design on Figure 6 for use in the experimental portion of Task II. The primary reason for this was that the photography of the extinguishment process was mandatory, and the availability of a truncated cone of glass at a reasonable cost proved to be an insurmountable problem. Thus, a cylindrical prototype was constructed by 12-inch diameter Pyrex pipe for the experiments. Other deviations from Figure 6 involved instrumentation for determining gas flow rate, a remote gas supply, and the use of supporting cables instead of the handle. No screen was used over the exhaust port of the test unit. A sketch of the test design is shown on Figure 7, and a photograph of the unit is presented as Figure 8.

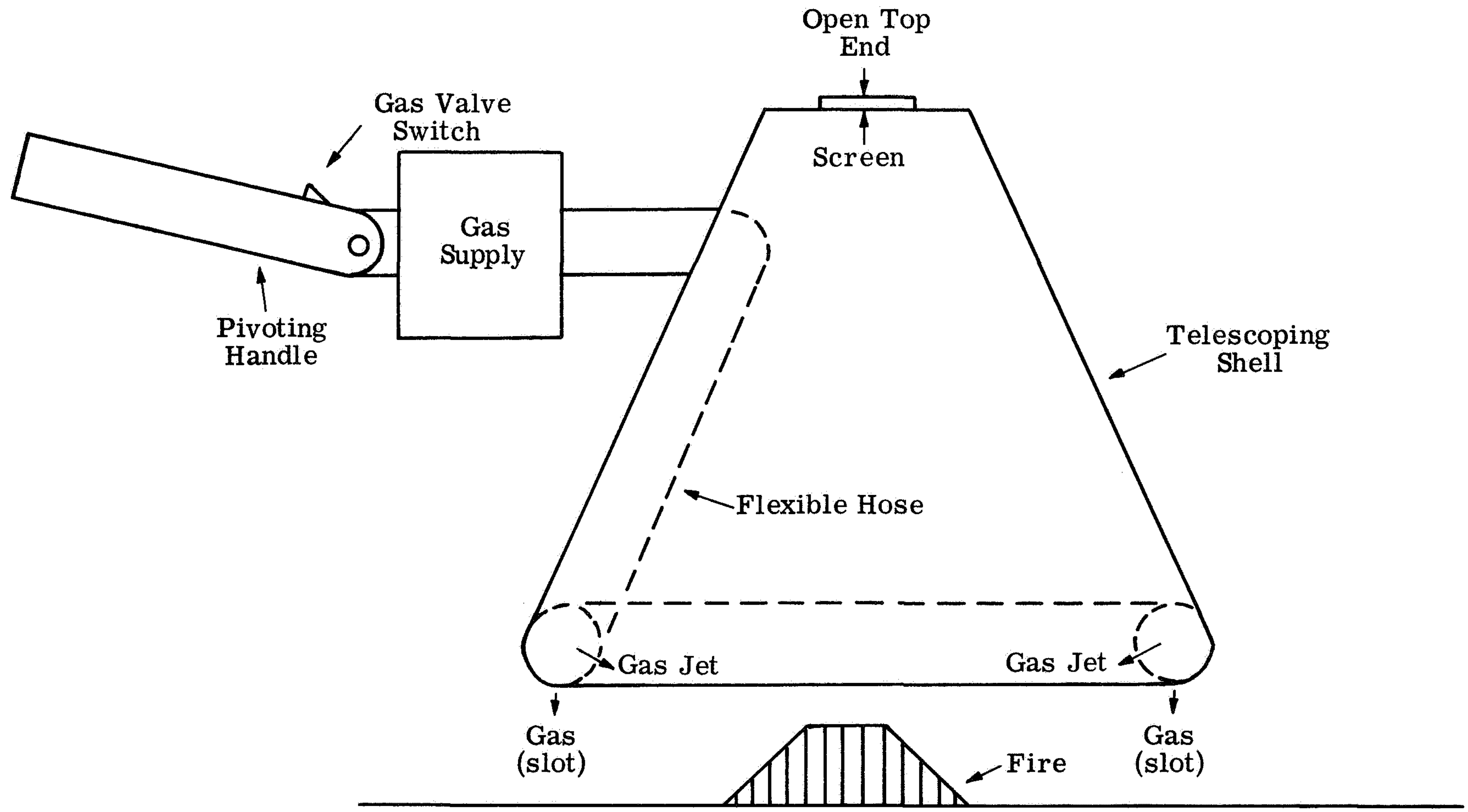

Figure 6. Conceptual Sketch of Fire Extinguisher (not to scale).

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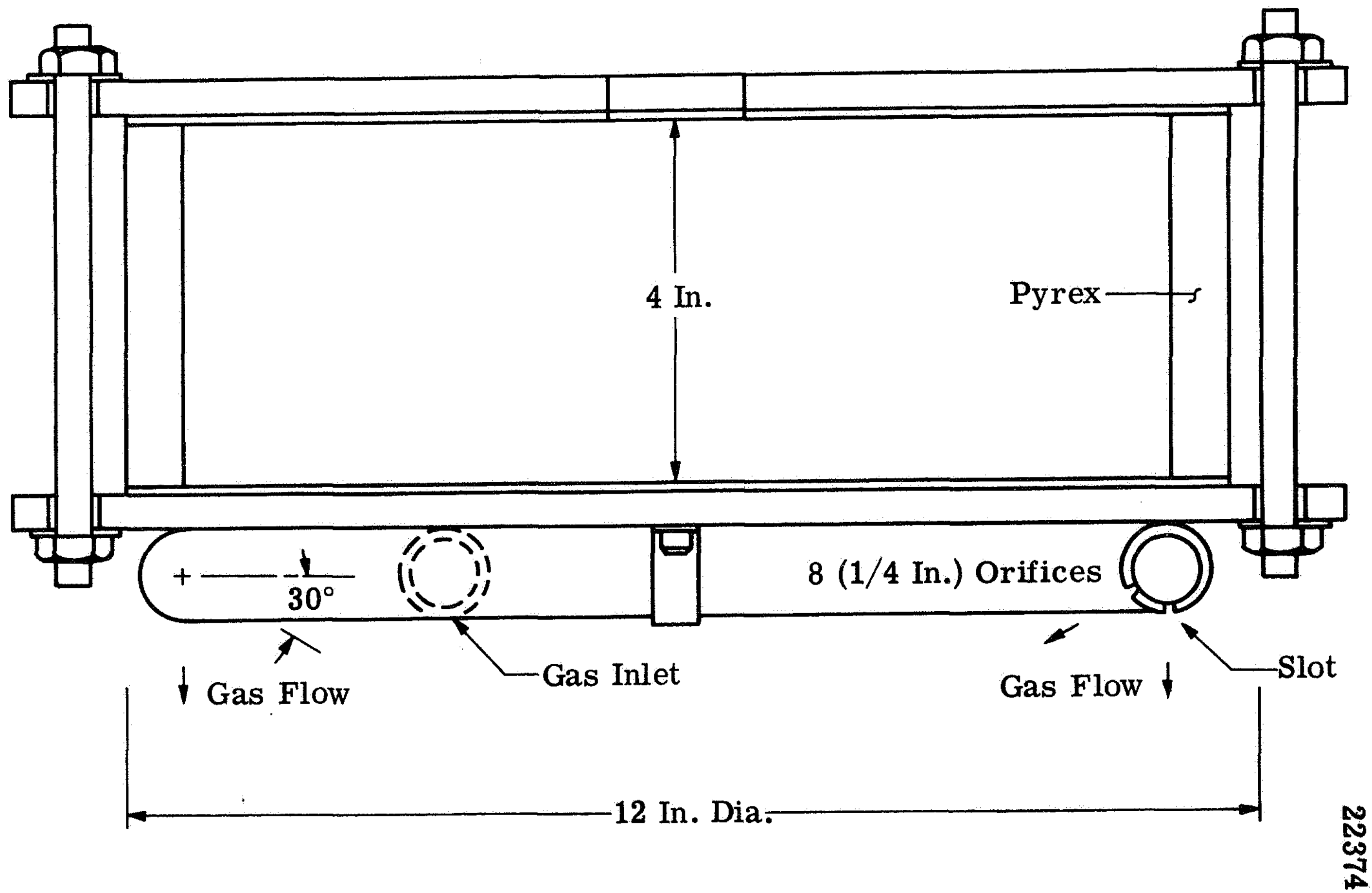

Figure 7. Hand-Held Extinguisher Test Design.

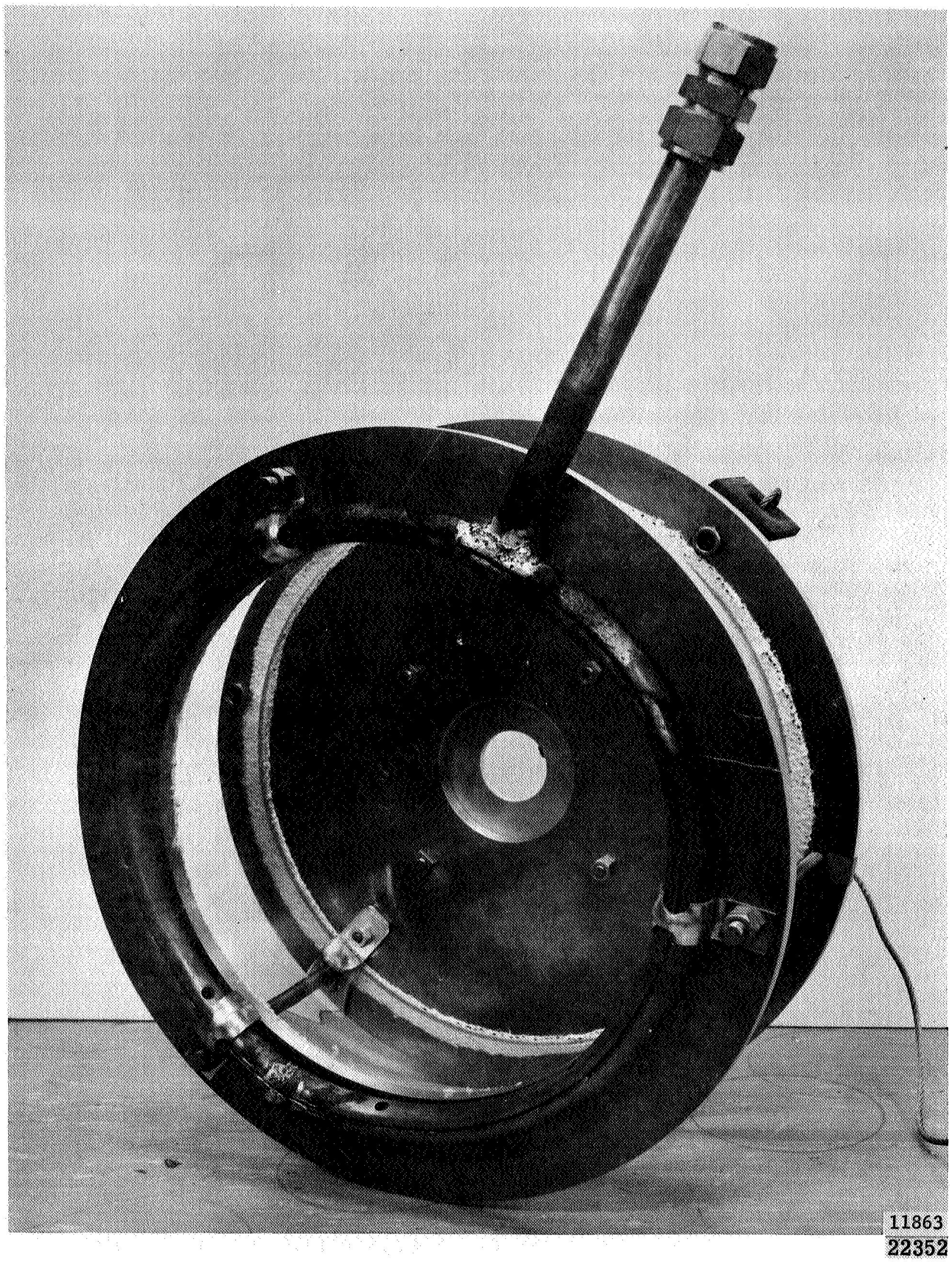

Figure 8. Photograph of Extinguisher Test Unit.

The extinguisher body, ref. Figure 8, was a 12-inch-diameter, mold-blown Pyrex cylinder measuring 4 inches in length. Wall thickness was nominally 0.5 inch. The cylinder was capped with a 14.5-inch-diameter aluminum plate, 0.375-inch thick. A 1.5-inch-diameter exhaust port was centrally located. Provision was made to adapt ports of diameters less than 1.5 inches. An annular aluminum base plate, 14.5-inch O.D., 10.375-inch I.D., and 0.375-inch thick, provided a mounting surface for a 0.50-inch-diameter copper torus. A 0.062-inch circumferential slot in the torus exhausted the extinguishing gas to form a curtain which provided isolation of a small flame. Eight equally spaced 0.25-inch-diameter orifices were drilled so as to direct streams of inert gas downward 30 degrees from the horizontal axis. Asbestos gasketing was utilized at the cylinder-plate interfaces. The components were assembled, as illustrated, and secured with 3/8-24 threaded rod.

3.3 EXPERIMENTAL SYSTEMS AND PROCEDURES

3.3.1 Experimental Systems

The subject developmental tests have been conducted using the Atlantic Research Vacuum Facility and an attached test chamber with an approximate volume of 130 cubic feet. Table IV, "Test Chamber Specifications", describes the test chamber in detail. Two flanged ports were provided with a 10-inch clear diameter to allow visual test observation simultaneous with photographic coverage, and remote positioning of the test sample and extinguisher. The laterally located observation port, ref. Figure 9, was fabricated using a sandwich construction comprised of two 0.5-inch plates of acrylic backed with 0.25-inch thick glass plate. The glass was in-board. The remote positioning window, located aft on the test chamber longitudinal axis, was fabricated of two 0.5-inch discs of acrylic to facilitate passage of remote control rods. Port seals utilized flat Neoprene rubber gaskets. Internal steel Uni-Strut channels, P-1000, provided a convenient mounting surface for internal test components. Two, six-inch diameter instrumentation ports were provided. Power leads were

TABLE IV

Test Chamber Specifications

Shell Diameter:	4 ft.
Length:	10 ft., horizontal
Working Pressure:	125 psi @ 450°F and full vacuum
Construction:	ASME code. welded steel shell.
Access:	Quick opening, hinged head.
Head Type:	Domed
Bottom:	Round
Observation Ports:	(2) 10 in. diameter
Instrumentation Ports:	(2) 6 in. diameter
Internal Mounting:	Uni-Strut Channel
Portable:	(4) non-locking swivel casters, 2000 lb. load rating ea. Overall height: 7-5/8 in.

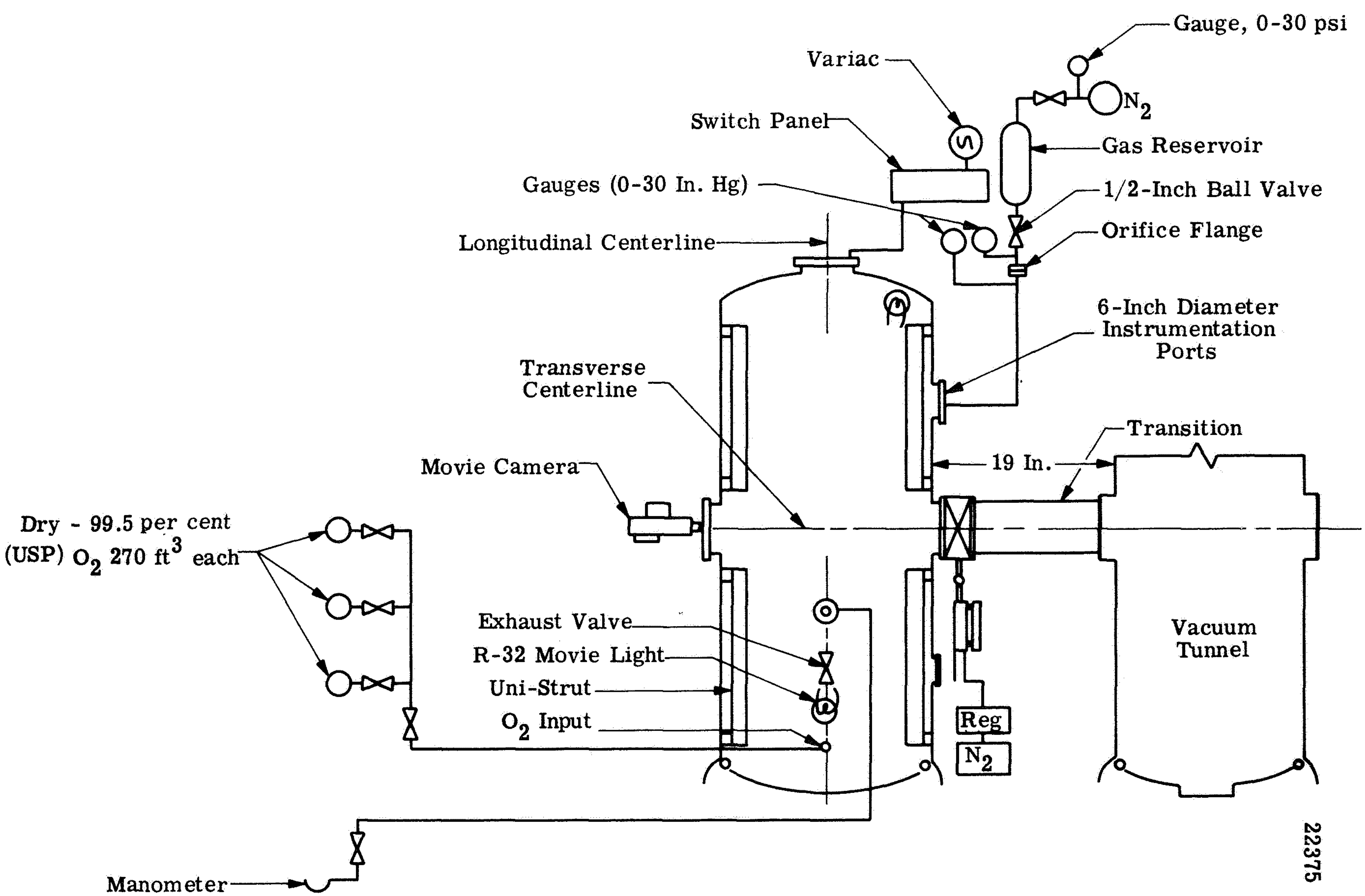

Figure 9. Schematic of Test System.

fed thru the aft port. Internal duplex receptacles provided power to two R-32 photoflood lamps.

The test chamber was vented to the vacuum tunnel through a 10-inch I.D. flanged port, located diametrically opposite the side observation port. A 10-inch diameter pneumatically-operated, solenoid-actuated, butterfly valve controlled venting to the vacuum tunnel. A gas reservoir was included in this system to permit fast response. A 10.5-inch length transition section with welded slip-on flanges connected the valve to the vacuum tunnel. Overall inter-connection length was 19 inches. All seals were Viton O-Rings.

The test chamber gas supply system consisted of three 270 scf bottles of dry - 99.5% pure (U.S.P.) oxygen. Test chamber pressure level was monitored by a u-tube mercury manometer. A single 251 cu. ft. bottle of oil-free nitrogen supplied the extinguishing gas. A gas reservoir (surge tank) was included in this system to permit fast response. Initiation of extinguishing-gas flow was controlled by a 0.5-in. Jamesbury ball valve. A thin-plate orifice (0.144 in. diam.) measured gas flow rate.

Camera and igniter power were obtained from outlets located adjacent to the test chamber. Camera actuation and igniter selection were controlled at a switch panel mounted near the remote positioning port.

The test chamber was connected to the High Altitude Facility. The "vacuum tunnel" section consisted of a stainless steel cylinder measuring six feet in diameter and 25 feet long, which was exhausted by a five-stage steam ejector system. The facility has a design pumping capacity of 71,000 liters of air per second at a pressure of 60 microns of mercury, which simulates an altitude of approximately 245,000 feet. The ejectors use 9,000 pounds of steam per hour and the two condensers require 1200 gallons of cooling water per minute. Direct-contact type condensers are located between the third and fourth stages and between the fourth and fifth stages. The condensers are used to reduce the overall steam consumption of the unit. The steam is supplied by a gas-fired, automatic boiler with a rated output of 10.35 MBTU/hr. A preheater using steam as the heat source is used to preheat the boiler feed water to approximately 190°F.

3.3.2 General Operational Procedures

The purpose of the tests accomplished to date has been to determine extinguishing-gas flow rate, for the handheld device, as a function of time to combustion termination. The experimental procedures were outlined below:

A. Preparation

1. Mount igniter and check operation. Establish proper power level setting.
2. Mount test sample.
3. Align test sample and extinguisher. The camera view of the sample must not be obstructed by the extended extinguisher.
4. Camera: load, set proper focus, f-stop, frame speed and lighting.
5. Calibrate film framing rate.
6. Obtain test identification on film.
7. Film sample before test.
8. Seal test chamber, evacuate chamber and extinguishing-gas flow system.
9. Secure vacuum tunnel pumping port.
10. Charge chamber with test atmosphere.
11. Establish and check flow rate parameters.

B. Test

1. Countdown

   (4) Camera on, lights on as required.

   (3) Igniter on.

(2) Igniter off.

(1) ---------

(0) Lower extinguisher to within 0.5 in. of test tray. Simultaneously (with same switch) initiate timer and extinguishing gas flow.

2. Monitor extinguishing-gas flow rate parameters.

3. Log elapsed time to termination of combustion.

4. Secure extinguishing-gas flow.

5. Secure camera.

6. Log flow-rate parameters.

7. Film sample after test.

8. Vent test chamber.

Note: Two more samples could be tested with a fresh charge of oxygen without the necessity of entering the chamber.

3.3.3 Experimental Apparatus

The design of the experimental apparatus accomodated the investigation of several factors including: (1) effects of gas type and gas flow rate on extinguishment times and total amount of gas used; (2) effect of flame size and fuel type on extinguishment; and (3) effects of extinguisher design and environmental geometry on the effectiveness of flame isolation and extinguishment.

Test chamber and extinguisher dimensions conveniently permitted the burning of three successive test samples. The samples were equally spaced on the longitudinal axis of a 48" x 19" x 0.281" aluminum sample tray. The tray axis was situated 7.625 inches below the test-chamber longitudinal axis. The plane of the tray was horizontal. The test samples were readily secured to the tray by means of stationary-type spring clips. The sample tray sides were arranged to slide on Uni-Strut channels. Alignment of a bolt placed opposite each test sample with a bolt on the Uni-Strut channel assured proper sample location relative to the camera field of view from the test-chamber lateral observation port. Remote positioning of the test sample tray was accomplished by means of a push rod secured to a tray extension and extending aft through the remote positioning window.

Sample ignition was accomplished by resistance heating 24-gage coiled Nichrome wire, positioned at 45° to the sample axis and in contact with the upper sample surface. Suitable power level setting was secured by operation of a Variac located adjacent to the camera-igniter switch panel.

The extinguisher was suspended opposite the lateral observation port by wire rope passing through an overhead pulley, as shown on Figure 10. The wire rope was, in turn, secured to a second longitudinal push rod, extending aft through the remote positioning window. The push rod was provided with a cushioned stop to facilitate extinguisher positioning 0.5 inch above the sample tray. Extinguishing-gas feed to the slotted torus was via a flexible hose, so weighted as to maintain a horizontal extinguisher orientation during translation.

Internal duplex receptacles provided power to two R-32 photo-flood lamps.

Movies at 12 frames per second were obtained with a Bolex camera mounted at the test-chamber lateral observation port.

Before each test the test chamber was evacuated to a pressure of 60 microns through the connection to the vacuum tunnel. The evacuated chamber was then isolated from the vaccum tunnel and was charged with USP (99.5 per cent), dried oxygen gas to a final pressure of 5 psia. Thus, the initial atmosphere in the test chamber for all of the extinguishment tests was 99+ per cent oxygen.

3.3.4 Determination of Inert Gas Flow Rates

The flow rates of the inert gases corresponding to the four values of upstream pressure used were calculated from the ASTM working formula[8] as follows:

$$w = KYS_2 \sqrt{2g_c(p_1-p_2)(\rho_1)}$$

where: w = rate of discharge (lb/sec)

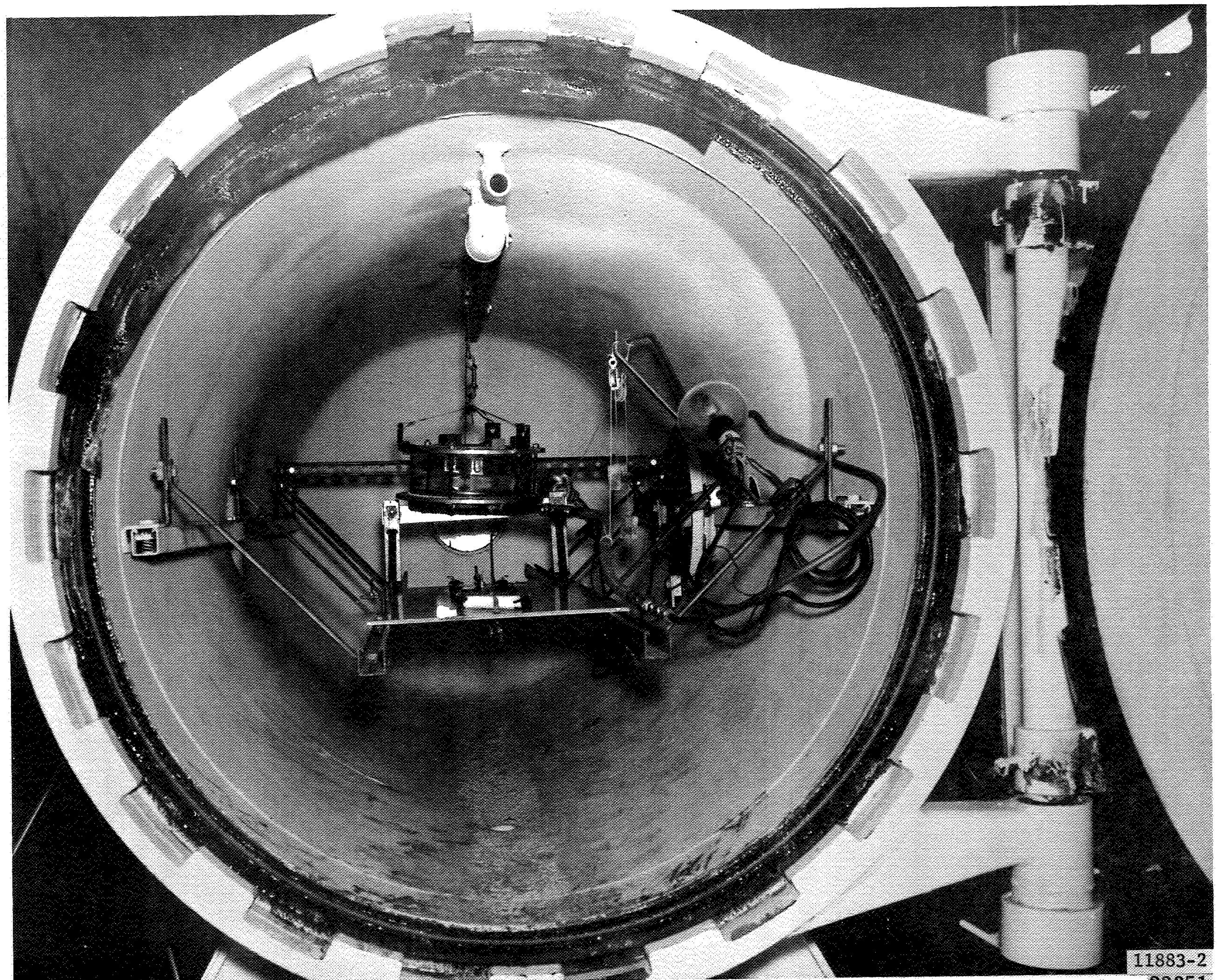

Figure 10. Experimental Assembly in Test Chamber.

K = discharge coefficient divided by $(1-\beta^4)$ - where β = diameter ratio of tube to orifice - the value of K was taken as 0.61 (dimensionless)

Y = expansion factor (dimensionless) = 0.90 (see Ref. 8)

S_2 = orifice cross-sectional area (sq. ft.)

g_c = gravitational constant - 32.2 $(lb_m)(ft)/(lb_f)(sec^2)$

p_1 = pressure upstream of orifice (lb_f/sq ft)

p_2 = pressure downstream of orifice (lb_f/sq ft)

ρ_1 = fluid density upstream of orifice (lb_m/cu ft)

The calculation of flow rates was checked with one calibration at a pressure drop of 30 lb/sq. in. According to the above equation the volumetric flow rate was 10.3 scfm, and the experimentally determined value was 10.5 scfm. This excellent agreement validates the use of the calculational procedure in this calibration.

The experimentally determined value of 10.5 scfm was obtained by passing nitrogen through the orifice into a chamber of known volume (130 cu. ft.) for 30 sec at 68°F. The pressure change caused by the addition of gas was 0.67 lb/sq. in. Correction to standard conditions was based on relationships for a perfect gas.

3.4 EXPERIMENTAL CONDITIONS AND RESULTS

3.4.1 Extinguishment of Flaming Plastic Rods

The first series of tests performed with the extinguisher of Figure 8 consisted of determining the effect of nitrogen flow rate upon extinguishing times for flaming samples of 1/4-inch diameter plastic rods. The three materials used were nylon, polycarbonate, and polymethylmethacrylate (polyacrylic). In these tests each rod was ignited in the middle of the six inch long sample, the flame was allowed to cover the entire length, and then the extinguisher was lowered to within 0.5 inch of the surface on which the rod was placed.

Initiation of gas flow occurred simultaneously with the dropping of the extinguisher unit. Times to extinguishment were determined from motion picture coverage as the time span between dropping the extinguisher and the absence of visual evidence of flame. All tests were in an initial atmosphere of 5 lb./sq. in. pure (99+ per cent) oxygen, and no sample reignited after extinguishment.

The data from these tests are presented as Table V. The extinguishment times observed in these tests ranged from 2.8 sec. to 9.1 sec., but most values fell around five seconds. Since neither extinguishment times nor total nitrogen flow to extinguish exhibited a significant trend with gas flow rate, it must be concluded that the flow rate range was not wide enough (did not extend low enough) to allow such a trend. The only significant trend in the data of Table V was the variation in total flow to extinguishment as a function of material. The polyacrylic required the highest weight of gas for extinguishment, the nylon required the least, and the polycarbonate fell between the other two.

3.4.2 Extinguishment of Burning Plastic Foams by Nitrogen

It was believed that extinguishment of flaming plastic foams would prove to be a more severe test of extinguisher effectiveness than extinguishment of burning rods. Polystyrene (styrofoam) and open-cell polyurethane foams were used in these tests. In the first series of tests nitrogen gas was used at the same flow rates as were used for the rod extinguishment tests. The results of this series are presented in Table VI.

The data on Table V are similar to those on Table VI in that essentially no dependence of time to extinguish on nitrogen flow rate was found. In addition, the typical value of five seconds to extinguish the foam samples was similar to that observed with burning rods. However, the data on Table VI do indicate that total gas used decreased as flow rate decreased. Obviously, a flow rate of 0.0061 lb./sec. of nitrogen is not below the minimum gas flow corresponding to a minimum extinguishment time.

TABLE V

Extinguishment Times and Gas Weights for the Prototype Extinguisher of Figure 6 using Nitrogen Gas to Extinguish Flaming Plastic Rods 0.25-in. in Diameter by 6-in. Long (Original Atmosphere 5 lb./sq.in. Pure Oxygen)

Test No.	Material	N_2 Flow Rate (lb/sec x 10^2)	Extinguishment Time (sec)	Total N_2 Flow to Extinguish (lb)
8	Nylon	1.34	2.8	0.038
11	Nylon	0.92	6.0	0.055
14	Nylon	0.72	4.5	0.032
26	Nylon	0.61	6.6	0.040
29	Nylon	0.61	4.0	0.024
7	Polyacrylic	1.34	4.0	0.054
10	Polyacrylic	0.92	7.5	0.069
13	Polyacrylic	0.72	6.8	0.049
25	Polyacrylic	0.61	8.4	0.051
28	Polyacrylic	0.61	5.5	0.034
9	Polycarbonate	1.34	2.5	0.034
12	Polycarbonate	0.92	9.1	0.084
15	Polycarbonate	0.72	7.4	0.053
27	Polycarbonate	0.61	5.0	0.031
30	Polycarbonate	0.61	4.5	0.027

Note - No more than about 15 per cent of the fuel (sample) was consumed in any of these tests.

TABLE VI

Extinguishment Test Results for Plastic Foams using Nitrogen Gas in Prototype Extinguisher
(Original Atmosphere 5 lb./sq. in. Pure Oxygen)

Test No.	Sample Materials	Dimensions (in)	N_2 Flow Rate (lb/sec x 10^2)	Extinguishment Time (sec)	Total N_2 Flow (lb)	Sample Wt. Loss (gm.)	Fraction of Weight Lost (per cent)
31	Polystyrene	6 x 0.9 x 1	1.34	5.8	0.078	0.35	13.5
34	Polystyrene	6 x 0.9 x 1	0.92	5.1	0.047	0.42	15.4
37	Polystyrene	6 x 0.9 x 1	0.72	5.7	0.041	0.36	13.5
40	Polystyrene	6 x 0.9 x 1	0.61	6.6	0.040	0.30	11.3
32	Polyurethane (open-cell)[a]	6 x 1 x 0.4	1.34	3.5	0.047	0.24	16.2
35	Polyurethane (open-cell)[a]	6 x 1 x 0.4	0.92	3.7	0.034	0.45	30.9
38	Polyurethane (open-cell)[a]	6 x 1 x 0.4	0.72	4.9	0.035	0.57	38.0
41	Polyurethane (open-cell)[a]	6 x 1 x 0.4	0.61	5.4	0.033	0.30	37.1
33	Polyurethane (open-cell)[b]	6 x 1 x 1.75	1.34	5.2	0.070	1.18	22.6
45	Polyurethane (open-cell)[b]	6 x 1 x 1.75	1.34	2.6	0.035	1.02	18.3
36	Polyurethane (open-cell)[b]	6 x 1 x 1.75	0.92	4.9	0.045	1.43	23.5
39	Polyurethane (open-cell)[b]	6 x 1 x 1.75	0.72	6.7	0.048	1.22	22.4
57	Polyurethane (open-cell)[b]	6 x 1 x 1.75	0.61	5.3	0.032	1.69	32.9
58	Polyurethane (open-cell)[b]	6 x 1 x 1.75	0.61	3.1	0.019	1.73	33.1
59	Polyurethane (open-cell)[b]	6 x 1 x 1.75	0.61	3.5	0.021	1.22	20.3

[a] Black color (self-extinguishing in air)

[b] White color (not self-extinguishing in air)

Prior to initiation of nitrogen flow the foam samples were ignited approximately at the center of their six inch length, and the flame was allowed to cover the sample. Thus, the weight losses on Table V are higher than those which occurred during the extinguishment portion of the test. It is interesting to note that less of the styrofoam was consumed compared with the polyurethane, but that the polystyrene samples were greatly altered dimensionally compared to the polyurethane. Photographic comparisons of typical samples are presented as Figures 11, 12 and 13.

In this work the lower limit of the controllable pressure drop was set by the instrumentation available to the program. However, even though the optimum flow rate does not appear to have been obtained, the data presented in Tables V and VI are believed sufficient to establish the feasibility of the type of extinguisher design used. No burning fragments were observed leaving the "chimney" of the extinguisher mock-up used, even though no screen was used to prevent their escape. However, a direct flow of 0.0134 lb./sec. of nitrogen from a nozzle located 12 inches above a sample of flaming polyurethane (6.3 in. x 1 in. x 1.75 in.) spread burning fragments throughout the chamber, and the "extinguishment time" for the sample was 54.4 seconds. Actually, this time represented essentially the total burn time (all fuel consumed) less the time between ignition and initiation of gas flow.

3.4.3 Extinguishment with Other Gases

Several tests were performed using argon and carbon dioxide as the extinguishing gas. Procedures were similar to those described previously. The initial atmosphere was 5 lb./sq. in. pure oxygen, and the material used was the white open-cell polyurethane of 6 in. x 1.0 in. x 1.75 in. dimensions. A comparison of the test results for all three gases is presented on Table VII. The one test with carbon dioxide required a somewhat lower time to extinguish the flames than the tests with nitrogen or argon. Unfortunately, further tests with CO_2 could not be performed due to a major vacuum system malfunction. The total gas flow for CO_2 was also slightly lower than that for nitrogen at the 0.0061 lb./sec. flow rate condition. Since this difference could not be attributed to specific heats of the gases, it appears either that the values

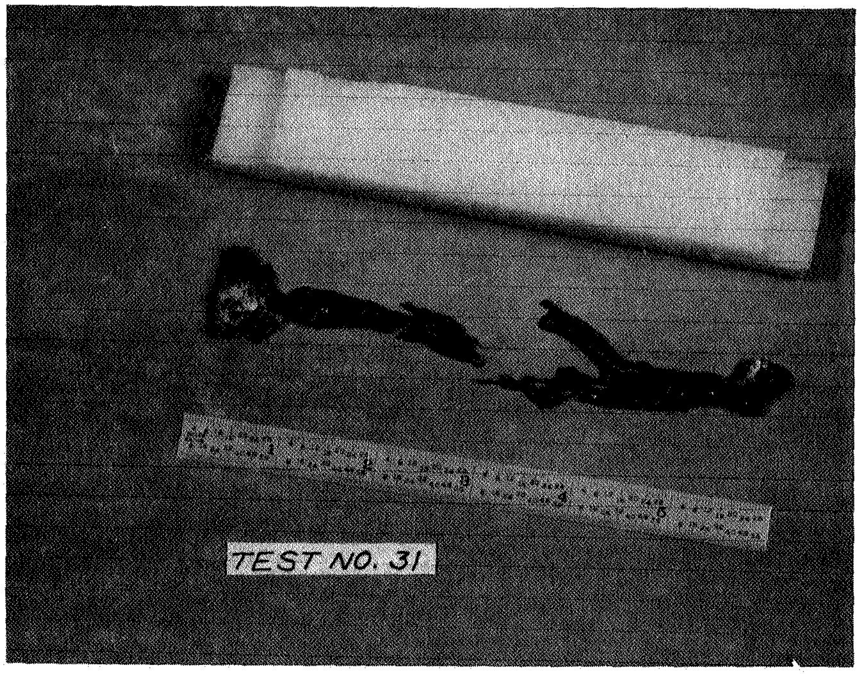

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Figure 11. Samples of Polystyrene Before and After Extinguishment Test.

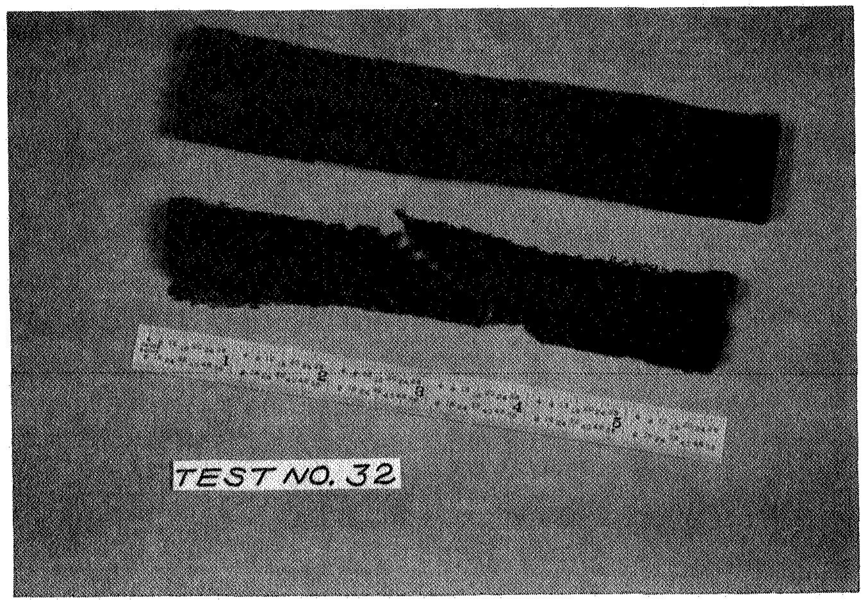

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Figure 12. Samples of Black Open-Cell Polyurethane Before and After Extinguishment Test.

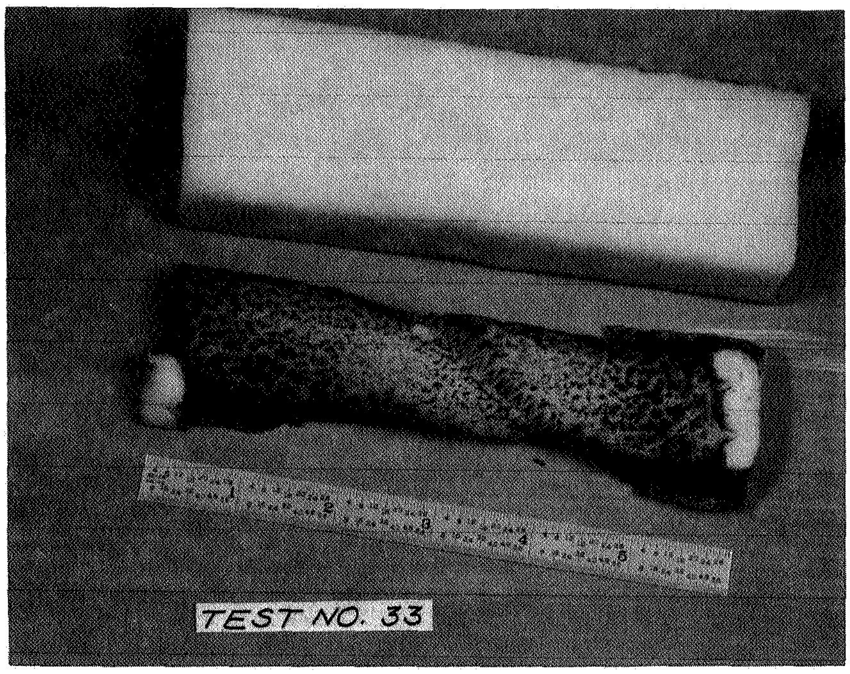

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Figure 13. Samples of White Open-Cell Polyurethane Before and After Extinguishment Test.

TABLE VII

Comparison of Extinguishment Test Results on Burning Polyurethane Foam for Three Inert Gases (Original Atmosphere 5 lb./sq.in. Pure Oxygen)

Test No.	Gas	Flow Rate (lb/sec x 10^2)	Extinguishment Time (sec)	Total Gas Flow (lb)	Gas Temperature (°F)	Specific Heat of Gas (Btu/lb - °F)[b]
36	N_2	0.92	4.9	0.045	80	0.25
39	N_2	0.72	6.7	0.048	80	0.25
57 - 59[a]	N_2	0.61	4.0	0.024	80	0.25
60	A	0.72	4.5	0.032	70	0.124
61	A	0.72	4.9	0.035	70	0.124
62	A	0.72	3.8	0.027	70	0.124
63	CO_2	0.79	2.3	0.018	59	0.21

[a] Average values for tests 57, 58, and 59

[b] Determined at listed gas temperature

for CO_2 were unusually low or that the 20°F temperature difference between the N_2 and the CO_2 was important to the extinguishment. We believe that the difference in temperature was important. This temperature difference arose from the differences in the expansion process between the two gases.

3.5 DISCUSSION OF EXTINGUISHER TEST RESULTS

The test results presented in Section 3.4 demonstrate that inert gas can be used to effectively and efficiently extinguish fires in pure oxygen atmospheres, if the fire site can be isolated from the environment. However, a meaningful comparison of the general extinguisher design used in this program with present state-of-the-art extinguishment techniques is not now possible. The potential practicability of such an extinguisher for small on-board fires is also not known. There are several reasons for this, as follows: (1) the design is not optimized as to size, weight, gas flow rate, and gas type; (2) we are not aware of any work from which the trade-off between potential fire hazards on future spacecraft and extinguishment methods, extinguisher sizes, etc., can be determined; (3) it is not known whether future missions will utilize an atmosphere of pure oxygen or gas mixtures which would mitigate or eliminate potential fire hazards; (4) the critical distance between the extinguisher and the fire is not known; and (5) no flammables are presently located in spacecraft so that they could be "capped" or isolated, in this manner.

The choice of an inert gas for use in such an extinguisher may depend not only on the relative effectiveness in fire extinguishment, but also on what amounts of the various candidate gases could be tolerated in the cabin. In the case of nitrogen or argon there would probably not be available methods of removal, other than venting to space, so that the worst case would be for all of the inert gas to remain in the atmosphere. Carbon dioxide could be removed from the cabin atmosphere, but the amount released must not cause an overload of the CO_2 - removal system. Definition of useful designs can only follow considerably more tests using realistic situations of geometry and fuel to see if potential uses exist.

4.0 CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

The following conclusions are based on the experimental results obtained in this program:

(1) Quenching distances for flaming solids are strong functions of atmosphere, sample material, and geometry, but the upper limit of such quenching distances is about 1/2 inch.

(2) This limit of quenching distance corresponds approximately to the maximum partial pressure of oxygen for which the material will not ignite.

(3) Polymer films backed by a heat sink surface (vertical orientation) will not propagate flame in 258 mm Hg pure oxygen when the film thickness is below a certain value determined by the material. This critical film thickness for nylon, polycarbonate, and polyacrylic is approximately 1/64-inch.

(4) Inert gas is an effective extinguishing agent for fires in pure oxygen when the fire can be effectively isolated.

(5) The extinguisher design used in this program can extinguish flaming samples of plastic foams within five seconds using nitrogen, argon, or carbon dioxide. The design is, however, limited to relatively small fires in accessible locations.

4.2 RECOMMENDATIONS FOR FUTURE WORK

Recommendations as to future work on the topics discussed in this report are listed as follows:

(1) It is recommended that the use of thin plastic films protected by a heat sink backing be further investigated, and that criteria for their use (without hazard) in pure oxygen atmospheres be established.

(2) It is recommended that the fire extinguisher design used in this program be optimized as to gas flow rate, geometry, and gas type.

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