SCREENING OF FLAME-RESISTANT MATERIALS

and

COMPARISON OF HELIUM WITH NITROGEN FOR USE IN DIVING ATMOSPHERES

First Annual Summary Report on

Combustion Safety in Diving Atmospheres

Contract No. N00014-66-C0149

OFFICE OF NAVAL RESEARCH, U.S. NAVY

by

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March 31, 1967

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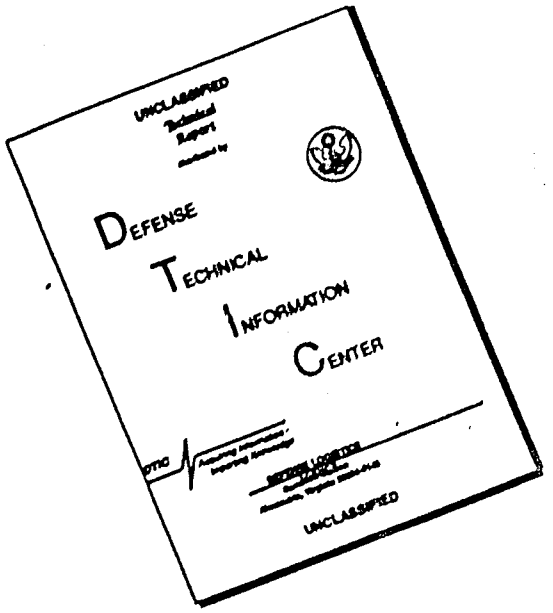

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FOREWORD AND AUTHORIZATION

This is the technical report on the work carried out over the period April 1, 1966, through March 31, 1967, in the Research Laboratory of Linde Division, Union Carbide Corporation, Tonawanda, New York, under

Contract No. N00014-66-C0149

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This contract was funded by the Office of Naval Research and by the Ship Systems Command (formerly the Bureau of Ships), U.S. Navy, and was monitored by Lieutenant Commander John V. Harter of the U.S. Navy Experimental Diving Unit, Building 214, Washington Navy Yard, Washington, D. C., 20390.

The Administrative Officer in the Office of Naval Research was Commander F. L. Crump, Director, Surface and Amphibious Programs. Lieutenant Commander T. W. Robinson was the Cognizant Scientific Officer for ONR.

The Principal Investigator for the contract was Gerhard A. Cook, Ph.D. Most of the laboratory work was carried out by Robert E. Meierer. Bruce M. Shields acted as consultant and also helped in the direction and carrying out of the experimental work.

A great deal of interest in both the inception and the progress of this work has been shown by Dr. Heinz R. Schreiner of the Linde Research Laboratory, under whose direction various other aspects of diving activities are being investigated in cooperation with Ocean Systems, Inc. Dr. Schreiner and Dr. R. W. Hamilton have acted as consultants on diving technology for this project.

The pressure vessel, including the closure which makes it possible to carry out the experiments rapidly and conveniently, was largely designed by Warren O. Bath. Helpful suggestions were made by Oren E. Berwaldt and Robert F. Dwyer. Hugh E. Nevins suggested some empirical mathematical models and carried out the computer programming.

We are grateful to the companies that supplied samples for testing and information about their products; we have noted these contributions individually, and we hope that the companies will let us know if we made any errors.

Persons knowing of flame-resistant materials, of published papers, or of reports that are of significance in connection with this investigation and that are not covered in our literature survey, are asked to write to Dr. G. A. Cook, Linde Division of Union Carbide Corporation, P.O. Box 44, Tonawanda, N. Y., 14150, or to telephone him on 716-877-1600, Extension 446. Comments on this report will also be welcome.

ABSTRACT

The main purposes of the study carried out during the first year of this contract were: (1) to determine the influence of sample angle, ambient-gas composition (air, oxygen-enriched air, pure oxygen, oxygen-nitrogen mixtures, and oxygen-helium mixtures) and pressure (0 to 1000 fsw) on the burning rate of a typical combustible material, and (2) to procure samples and make a preliminary evaluation, by means of small-scale tests, of fire-resistant or non-combustible textiles, elastomers, insulation etc. which might be useful in diving-decompression chambers. It is expected that the information developed under this contract will be of value, not only in diving, but also in space-simulation chambers, space vehicles, therapeutic oxygen tents, and the hyperbaric oxygen chambers used in some hospitals.

The experimental results show that under most conditions, everything else being equal, burning takes place more rapidly when helium, rather than nitrogen, is the oxygen diluent.

Samples of over 60 different materials were procured, tested, and tentatively assigned to one of ten classes with respect to fire resistance.

The report also includes a survey of literature published too late to be included in the extensive review by Roth [48] that appeared in 1964.

ABBREVIATIONS AND SYMBOLS

[ ]	=	Used to enclose literature reference numbers, or our comments (as contrasted with information from outside sources)
%	=	Mole-% when used in stating gas composition
A.A. atm. abs.	=	Atmospheres absolute (pressure)
atm	=	Atmosphere
Btu	=	British thermal unit(s)
C	=	Celsius (formerly Centigrade)
cm	=	Centimeter
F	=	Fahrenheit
Fig(s)	=	Figure(s)
fsw	=	Feet of seawater. Each foot of seawater = 0.445 lb./sq.in.
g	=	Gram(s)
I.D.	=	Internal diameter
psi psia psig	=	Pounds per square inch (absolute, gage)
PVC	=	Polyvinyl chloride
temp.	=	Temperature
mJ	=	millijoules
p, pp	=	page(s)
P_{O_2}	=	(partial) pressure of oxygen

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SCREENING OF FLAME-RESISTANT MATERIALS

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Combustion Safety in Diving Atmospheres

I. SUMMARY AND CONCLUSIONS

A. Survey of the Literature

The pertinent literature has been examined. A summary (Section IV below) is given of information contained in papers and reports not covered in the extensive review published by Roth [48] in 1964.

B. Equipment, Gas Mixtures, and Technique

1. Burning-rate measurements were made in a stainless steel pressure vessel (Figs. 6-13) 20 inches long by 6 inches in I.D. The vessel is so designed that it can be sealed either vacuum-tight or pressure-tight by turning the head closure one-eighth of a turn. This design makes it possible to carry out the tests conveniently and rapidly. The vessel is equipped with a high-pressure window.

2. Twenty-six different gas mixtures including nitrogen-oxygen, helium-oxygen, and nitrogen-helium-oxygen mixtures, were prepared in standard, high-pressure gas cylinders. The gases were analyzed by gas chromatography, and the percent oxygen was independently checked on an Orsat gas analyzer. The gases were used for studying the influence of gas composition on the burning rate of a standard material, viz., strips of filter paper.

3. As a standard, reproducible, and readily combustible material for carrying out the preliminary combustion-rate measurements in compressed air and the measurements on the relative burning rates in nitrogen-oxygen vs. helium-oxygen mixtures, we selected Whatman Filter Paper No. 1, made in England by W. and R. Balston Ltd. We used strips 6 mm wide

by about 160 mm long; the width was controlled closely (± 0.05 cm), but the exact length did not matter, because the rate of combustion was measured between thermocouple junctions which were always mounted in the same positions.

4. Samples of flame-retardant fabrics, elastomers, etc., were supplied to us by various companies. The materials are described in this report, and their source acknowledged.

C. Combustion in Compressed Air

1. The ignition temperature (Table 5) and the burning rate (Fig. 16) of strips of filter paper were measured in air at pressures ranging from atmospheric (0 fsw) to 300 fsw, the sample being held at various angles ranging from horizontal (0° angle) to vertical (90° angle).

2. The temperature required to ignite paper in compressed air fell rapidly as the pressure was increased (Fig. 17).

3. When one speaks about the effect of pressure on burn rate, it is necessary to specify the angle of the burning material. In the horizontal position there was little or no increase in burning rate as the pressure was increased (Fig. 16). At greater angles the burning rate increased appreciably as the pressure became greater, at least up to a pressure of 300 fsw, and the rate of this increase became larger as the angle became larger, up to 45°; then the rate of increase with increasing pressure started to fall off. In the vertical position, the burning rate was erratic.

In the vertical position, combustion cannot be measured in the same way as at lower angles. The flame (seen through the window of the pressure vessel) moves upward along the edges of the paper at high speed and then burns inward toward the center of the paper along the whole length of the paper at the same time. This is in contrast to the results obtained at smaller angles, where the flame moves from the bottom to the top of the paper, consuming all the paper as it passes upward.

4. In any given position except the horizontal, the burning rate at first increases as the total pressure is increased; however, the rate of this increase becomes progressively less, until at pressures somewhere above 300 fsw the rate levels off (Fig. 21). It is possible that, at sufficiently high pressures, the rate may even start to fall; enough work at higher pressures has not yet been done to be sure of this.

5. The hazard presented by the possibility of fire in a chamber filled with compressed air increases as the air pressure increases for two reasons: (a) the higher the pressure, the greater is the ease of ignition of combustible material, and (b) the higher the pressure, the greater (except in the horizontal position) is the rate of combustion. The hazard is greatest when flammable material is so located within the chamber that combustion is propagated vertically.

D. Effect of Gas Composition on the Burning Rate

In order to compare the rates of combustion in pure oxygen, oxygen diluted with nitrogen, and oxygen diluted with helium, 345 separate tests were made with strips of filter paper in the 26 different gas mixtures at pressures ranging from 0.21 atm. abs. to 10.1 atm. abs. (The upper end of this range corresponds to 300 fsw.) The results were correlated both graphically and with the aid of a computer. The principal conclusions reached from this study were:

1. The burning rate depends primarily on the partial pressure of oxygen and on the percentage of oxygen in the gas surrounding the combustible material; the burning rate increases as the partial pressure and the percent of oxygen increase; see Figs. 22 and 23.

2. As is the case for compressed air, and regardless of whether the diluent is helium or nitrogen, the rate of increase of the burning rate at an angle of 45° and at a constant percent of oxygen (at least up to a pressure of 300 fsw) becomes smaller as the pressure increases.

3. At total pressures ranging from 0 to 200 fsw, the burning rate (R_{He}) when helium is the diluent is usually higher than the rate (R_{N_2}) when nitrogen is the diluent. However, the ratio (R_{He}/R_{N_2}) of the burning rates is actually a complex function of both the percent oxygen in the gas mixture and of the total pressure; this dual dependency is shown in Fig. 1.

4. The measured burning rates are fairly well reproduced by a pair of empirical equations, which together cover the whole range of conditions tested.

5. The principal sources of error in measuring the burning rates are probably connected with variation in the width, weight, and moisture content of the paper strips. These three factors were controlled as closely as practicable.

6. The reproducibility of somewhat over half of our measured burning rates was ±10%; and for about half of the rest, the reproducibility was within 20% (Table 11).

E. Region of Non-Combustion

1. It has been found that, when oxygen partial pressures are sufficiently low, no ignition or combustion of filter paper takes place. Between this condition and the condition under which ignition and burning take place readily, there is a borderline region in which ignition takes place only with difficulty, and the resulting flame is self-extinguishing.

These conclusions are illustrated in Tables 20-23. In much of the region of non-combustion there is still enough oxygen for human breathing and respiration. Some work remains to be done in defining the region of non-combustion.

2. A comparison of the results for helium and nitrogen as oxygen diluents shows that when helium is the diluent, borderline combustion takes place at somewhat higher oxygen concentrations, and the region of non-combustion is somewhat greater. This is in contrast to our finding that, for most of the conditions under which combustion takes place easily, burning rates are higher when the diluent is helium.

F. Comparison of Helium and Nitrogen As Oxygen Diluents

Use of helium instead of nitrogen as an oxygen diluent has the advantages that (a) helium makes ignition of flammable materials more difficult, (b) the region of non-combustion is somewhat greater, (c) a helium-containing gas mixture is less dense and therefore easier for the diver to breathe at high pressures, and (d) helium does not have a narcotic effect on divers, at least up to a pressure of 650 fsw. Two disadvantages in the use of helium are (a) the burning rate, once ignition has taken place, is usually higher and (b) a serious distortion of human speech (due to change in the pitch) takes place when the helium concentration is high.

G. Tentative Evaluation of Fire-Resistant Materials

The choice of materials for use in diving chambers, hyperbaric oxygen chambers, and other confined spaces to be occupied by humans depends partly upon appearance, comfort (e.g., capability of absorbing body moisture), price, availability, and the toxicity of pyrolysis and combustion products; but the first consideration should be the selection of a fabric that will be resistant to combustion under the conditions to be encountered.

Before a final choice is made, tests should be carried out on a sufficiently large scale to give a good idea of how

the material would behave in actual use. During the first year of this contract there has been time only for small-scale screening tests.

In this preliminary work, tests were made, whenever possible, on strips of the material about 12 mm wide and 160 mm long.

In assessing the ultimate hazard, the sample strips were burned in the vertical position. However, when comparisons between similar materials were to be made, the strips were usually mounted at an angle of 45°, because burning rates at 45° are lower and can be measured more accurately than at 90°.

The fact that 90° is the most hazardous position for fires can be readily seen by visualizing how fast cotton window curtains will burn when set afire in a home.

Materials that we have tested to date may be tentatively assigned to one of ten principal classes.

Class 0. Burns readily in air at atmospheric pressure.

Class 1. Has an appreciably higher ignition temperature and/or burns at an appreciably lower rate in air at 1 atm. abs. pressure than cotton cloth or paper. An example of a Class 1 material is wool.

Class 2. Non-flammable or self-extinguishing in air at one atm. abs. pressure.

Class 3. Self-extinguishing or burns slowly in air at a pressure of 100 fsw (4.03 atm. abs.).

Class 4. Self-extinguishing or burns slowly in air at a pressure of 200 fsw (7.06 atm. abs.).

Class 5. Is self-extinguishing or burns slowly in a mixture of 25% oxygen and 75% nitrogen at a pressure of 1 atm. abs.

Class 6. Self-extinguishing or burns slowly in a mixture of 30% oxygen and 70% nitrogen at a pressure of 1 atm. abs.

Class 7. Self-extinguishing or burns slowly in a mixture of 40% oxygen and 60% nitrogen at a pressure of 1 atm. abs.

Class 8. Self-extinguishing or burns slowly in a mixture of 50% oxygen and 50% nitrogen at a pressure of 1 atm. abs.

Class 9. Completely non-flammable, even in 100% oxygen at 1 atm. abs. pressure; e.g., Beta Fiberglas.

The materials tested up to the present time are tentatively classified as follows:

Cloth fabrics	Table 1
Elastomers and flexible tubing	Table 2
Insulation, pillow stuffing, and films	Table 3

H. Tentative Suggestions for Materials to be Used in Diving-Decompression Chambers

Lists of items that might be present in a decompression chamber, supplied by the U.S. Navy Experimental Diving Unit and by Linde Bioresearch and Ocean Systems, Inc., are given in Section XX.

Following is a list of the more common items, together with suggestions (based upon the work of the past year under this contract and upon information in the literature) for non-burning or flame-resisting materials from which these items might be fabricated.

1. Bathrobes. (a) Undyed (non-itching) Beta Fiberglas - Class 9; (b) Teflon - Class 8; (c) Terry-knit Nomex - Class 6; information from DuPont indicates that, although Nomex itself does not absorb water readily, its ability to absorb moisture can perhaps be improved by the method used to weave the cloth; (d) Dynel - Class 5. In case none of the above turn out to be satisfactory in practice, the fifth choice (e) is APO-treated cotton terry cloth - Class 3, or some form of Roxel - Class 2, but see "Caution" at the end of the Summary and Conclusions.

2. Blankets. The best warm blanket found so far is Mine Safety Appliances Fire-Retardant Wool Blanket, Part No. 04-12487 - Class 4. There are other, presumably warm, fire-retardant blankets on the market, but no sample of these has yet been received. An MSC-NASA engineer suggested that a super-safe blanket could be made by sewing asbestos layers between layers of Beta Fiberglas cloth. A possibility for implementing this suggestion is the use of experimental fabric D67054 as the asbestos material.

3. Books and magazines. These might be kept in a steel, or better yet, a stainless steel box except while in actual use. A possibility is to keep books and notebooks in a steel binder.

4. Carbon-dioxide scrubber. Flammable materials must be avoided. Perhaps Molecular Sieves can be used to adsorb the carbon dioxide. Molecular Sieves are inorganic zeolites, and are completely non-flammable - Class 9.

5. Clothing. A universal problem with all non-combustible or highly flame-resistant fabrics seems to be that none of them absorb moisture to any appreciable extent. It is probably best, therefore, for divers to wear APO-treated cotton - Class 3 or Roxel - Class 2, underwear. Outer garments can be made of (a) Beta Fiberglas - Class 9, (b) Teflon - Class 8, Nomex - Class 6, or (d) Dynel - Class 5, depending upon the flame-resistance required.

6. Electric Motors. These should be completely sealed to prevent contact with the atmosphere in the chamber.

7. Gaskets. Viton - Class 6. Teflon - Class 8 would be safer and should be used where possible, but the physical properties of Viton are perhaps better suited for use in making gaskets than those of Teflon. For other possible gasket materials, see No. 9, masks.

8. Hammocks. Beta Fiberglas - Class 9; Teflon cloth - Class 8; Dynel - Class 5 or Nomex - Class 6.

9. Masks for Oxygen Inhalation. Thiokol experimental carboxy nitroso rubber terpolymer - Class 9. Other possible highly flame-resistant rubbers are Kel-F or Fluorel, samples of which have not yet been received. Other fire-retardant rubbers are SE-9029 - Class 2, and Silastic S-2316U - Class 2. Face masks could perhaps be made from Hypalon - Class 3, but DuPont is not certain about this.

10. Mattress Filling. The U.S. Navy Experimental Diving Unit has been using fiber glass as mattress stuffing. If this proves to be satisfactory, it would probably be the safest material available for this purpose.

11. Mattress Ticking. (a) Teflon-coated fiber glass cloth - Class 8; (b) glass cloth coated with Silastic - Class 6; (c) any of the following Class 5 fabrics: Rovana coated with PVC, Wonder Shield - plain*, or Asbeston Style S/5670 FEL or S/6555 coated on one or both sides with PVC; (d) any of the following Class 3 fabrics: Grade 12 NP brattice cloth, APO-treated cotton ticking, or Wheeler Green cotton No. 60; or (e) THPC-treated cotton ticking - Class 2.

- -

*This material contains only about 5% flammable material which is difficult to ignite; the fabric may therefore be more fire-resistant than the other Class 5 fabrics.

12. Mattress Covers with a plastic or rubber coating that can be wiped off. (a, b, and c) are the same as for No. 11, mattress ticking; also (d) Grade 12 NP brattice cloth, or the standard Navy submarine mattress cover coated with rubber - Class 3.

13. Paper, toilet and writing. We have not yet tested anything for this application, but we plan to test a product advertised by the National Starch and Chemical Corp., New York. This material is called Fire-Tard, and is an emulsion of one part of vinylidene chloride copolymer to one part of antimony trioxide. Paper treated with this emulsion is said to gain strength and greatly increase flame resistance. If this (or a similar) treatment is not effective, the paper and pencils will have to be kept in a metal box when not in use. Toilet paper can be kept in a metal dispenser which exposes only a part of one sheet at a time.

14. Pillow slips. (a) White or brown Teflon cloth - Class 8; (b) Nomex cloth - Class 6; (c) Dynel cloth - Class 5; (d) APO-treated cotton - Class 3; or (e) THPC-treated cotton - Class 2.

15. Pillow stuffing. (a) The U.S. Navy Experimental Diving Unit is now using pillows filled with glass fibers. The filling has not yet been tested by us, but will be Class 9 unless an appreciable amount of organic matter is present. (b) Nomex or Havolite batts - Class 5. (c) Polyurethane flame-retardant foam - Class 2.

16. Rope. Nothing has yet been tested. A fire-resistant, strong rope could probably be made from Nomex or Dynel fiber.

17. Sheets, bed. Same as No. 14, pillow slips.

18. Shoes. It would probably be best for the divers to wear only gym shoes. The rubber soles could be made from one of the flame-resistant rubbers (see No. 9, masks, above), perhaps made electrically conducting by a suitable additive. The uppers could be made of uncoated asbestos cloth - Class 9; of brown Teflon - Class 8; Nomex - Class 6; Dynel - Class 5; APO-treated canvas or 50:50 Nomex-Roxel - Class 3; or THPC-treated canvas - Class 2.

19. Swim fins. See No. 9, masks (above).

20. Towels. APO-treated cotton terry cloth* or Roxel cotton terry cloth*. When not in use, the towels should be

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*Not tested by us in this form.

kept in a stainless steel or plain box, because even the best of the treated cottons is not fire-resistant in 25% oxygen. There is a possibility that terry-knit Nomex - Class 6, could be used for toweling. In general, Nomex does not absorb water very well, but the terry knit may improve this situation. Practical tests should be made.

21. Tubing, flexible, low-pressure. This is made of corrugated Teflon* without any covering; see Section XIII.

22. Tubing, flexible, high-pressure. This tubing* is made of Teflon covered with stainless steel braid, and is sold by at least three companies (see Section XIII).

23. Wire insulation, flexible. Kapton - Class 9, or ITT Type WTE 1930 A (or 1932 A) - Class 8.

24. Wire insulation, permanent. See wire insulation, flexible, above. Permanent wiring should be enclosed in stainless steel or steel conduits.

J. Caution

Experience has shown that: (1) fabrics which burn at a low rate when sample strips are rather narrow, may burn at a higher rate when the strips are wider, or, in general, when more material is on fire. (2) When fabrics depend for their flame-retardant properties on treatment by an additive rather than on an instrinsically flame-resistant composition, there is sometimes considerable variability in flame-resistance of different samples, even from the same supplier. Therefore it is recommended that when treated fabrics are to be employed under hyperbaric or oxygen-enriched conditions, samples from the actual batch to be used should be tested in advance under the proposed conditions. (3) A material which is non-burning or self-extinguishing in air at atmospheric pressure may not be at all safe in air at higher pressures or in even slightly oxygen-enriched atmospheres.

II. INTRODUCTION

A. The Problem

The investigation carried out under this contract had its origin in (1) the recent upsurge of interest in the exploration of the oceans and of the natural resources which they afford, (2) the need of the U.S. Navy and other organizations for the capability of sending divers safely to

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*Not tested by us in this form.

ever-increasing depths, and (3) a fatal fire experienced by the Navy.

At an ocean depth of 200 feet, divers must be supplied with breathing gas at a pressure of 7.06 atm. abs. If this gas is compressed air, the partial pressure of oxygen is about 1.5 atm., and that of nitrogen about 5.5 atm. If a diver is to descend to greater depths, helium is usually added to increase the gas pressure, because a further increase in the partial pressure of oxygen leads to oxygen toxicity, and greater pressures of nitrogen lead to nitrogen narcosis. Helium apparently has no narcotic effect. An additional advantage in the use of helium is that its density is much less than that of either nitrogen or oxygen; addition of helium therefore makes it easier to breathe the gas mixture.

At a depth of about 600 fsw, even helium mixtures become too dense for comfortable breathing. There are two possibilites if a diver is to operate freely at greater depths: he may breathe a mixture of hydrogen and oxygen, or he may breathe liquid water saturated with oxygen under pressure. Both of these possibilities are still in early stages of development.

After a dive has been completed, the diver must be slowly decompressed. Toward the end the decompression process is often hastened by enriching the gas mixture with oxygen. The presence of oxygen in concentrations higher than that in air increases the danger of fire in the decompression chamber. Although fires in decompression chambers are rare, they have occasionally been fatal.

The Navy conducts research on problems of deep-sea diving at various locations, one of which is the U.S. Navy Experimental Diving Unit in the Washington, D. C., Naval Yard. At this location on the 16th of February, 1965, two divers lost their lives when fire broke out in a decompression chamber. The circumstances surrounding this fire have been well described in a paper by Lt. Cmdr. John V. Harter [28], which is abstracted in Section IV below. The fatal fire pointed up the vital need to know more about the fire hazards that might be encountered by the divers.

The information obtained in our past and future investigations will also be useful in connection with hospital oxygen tents, hyperbaric oxygen chambers employed by some hospitals for the treatment of certain diseases, such as gangrene; and to some extent, at least, in space-simulation chambers and in space vehicles, where artificial breathing atmospheres must be furnished to the astronauts in closely confined quarters.

Other things being equal, the risk of injury or death from fire in an enclosed space from which there is no immediate

escape is much greater than the risk we ordinarily encounter in our everyday lives, even when the atmosphere is only air at ordinary pressure. When divers are being decompressed or hospital patients are being treated in a hyperbaric oxygen chamber, immediate escape is impracticable because of the physiological danger that a sudden decrease in pressure will bring about decompression sickness, "the bends." Fires must therefore be prevented if possible; or if this is impossible, they must be held to burning rates and locations at which they can easily and quickly be extinguished by water or by other means.

The presence of air at pressures greater than atmospheric, or of gas mixtures enriched with oxygen, add to the hazards of operating in a confined space. Under these conditions ordinary flammables can burn so rapidly that their use should be avoided as much as possible. Some flammables, such as writing paper, reading matter, and toilet paper, will have to be present, but at least the quantity of these in a confined space can be kept low, and the materials can be stored in steel containers when not in use. For most items, either non-flammable or flame-resistant substitutes can be found.

B. Limitations Imposed by Oxygen Toxicity and Nitrogen Narcosis

The facts that (a) prolonged breathing of oxygen at partial pressures greater than 1.5 atm. may lead to convulsions, and (b) that at pressures greater than 5.5 atm., nitrogen tends to produce narcosis, have helped in setting limits to the conditions under which our fire-hazard investigations should be carried out. The usual upper limits for partial pressures in our work have been 2.0 atm. of oxygen (Figs. 35 and 36) and 8 atm. of nitrogen.

C. Work Statement in the Contract

The purpose of the work as stated in the contract is as follows:

"The Contractor shall furnish the necessary personnel and facilities for and, in accordance with any instructions issued by the Scientific Officer or his authorized representative, shall conduct research in the area of combustion safety in diving atmospheres. It will acquire basic information on ignitability and combustion rates of a standard material under controlled conditions in diving and decompression atmospheres. The Contractor will determine the degree of risk (relative hazard) of typical materials in common usage in diving equipment and chambers, will identify substitutes for unacceptable materials, and formulate recommendations and specifications."

D. Notes

1. The companies that were kind enough to supply materials for testing are anxious to protect their registered trade marks. To avoid use throughout the text of quotation marks around names which represent these trade marks, a list is given in Section XX.

2. Section XX includes a table showing equivalent pressures in feet of sea water (fsw), lb./sq. in. absolute (psia), and atmospheres absolute. This table also shows partial pressures of oxygen in compressed air at various pressures.

III. FUTURE WORK

It is suggested that a continuation of the work reported herein include the following projects:

A. Retesting on a Larger Scale

Materials that were tested on a small scale in the past year and showed special promise should be retested in a larger vessel. Larger quantities of the materials should be used so as to simulate actual fire conditions more closely than is done in the small-scale screening tests. For this purpose, we plan to borrow a chamber from the U.S. Navy Experimental Diving Unit and to take moving pictures through the window.

B. Continued Testing of Materials for Flame Resistance

We will continue to explore new sources of available flame-resistant materials. When samples of these new materials are procured, they will be tested by the methods described in this report.

C. Encouraging the Development of New Materials

For example, the development laboratory of the Uniroyal Fiber and Textile Division is producing some potentially useful asbestos-containing fabrics for us to test.

D. Fabrication of Face Masks

Although in general we do not plan to sponsor actual fabrication of end-products, it appears that an exception

may have to be made in the case of masks for administering oxygen. Several companies have compounded for us samples of flame-retardant rubber from which masks might be made, but these companies are apparently not interested in the actual fabrication of masks from a flame-retardant rubber on an experimental basis.

E. Region of non-combustion

It is of interest to complete the work, begun under this contract, of exploring the conditions under which even easily flammable materials, such as wax paper and cotton Terry cloth, will not burn. It is planned to extend the test conditions to a depth of 1350 fsw, and to include neon and hydrogen along with nitrogen and helium as oxygen diluents.

F. Effect of Gas Composition on the Burn Rate

It is planned (a) to extend the work described in this report to include the measuring of burn rates to pressures of 1350 fsw, (b) to include neon and hydrogen in the diluents to be tested, (c) to improve the empirical correlation of the results, and (d) to explore the possibilities of correlating burn rates with physical properties, especially with the heat capacity of the gases, as pioneered by Huggett et al. [30].

G. Extension of Our Measurements to 1350 Feet

March 23-25, 1966, there was held in Washington, D.C., the Third Symposium on Underwater Physiology, sponsored by the National Academy of Sciences - National Research Council and the Office of Naval Research. In a talk on "Interactions of Factors Limiting Performance," Professor Edward H. Lanphier of the State University of New York at Buffalo, an expert on underwater physiology, stated that the limit of human performance under water probably far exceeds the 1000-foot depth. While it is true that diving to 1000 feet is a more immediate goal than diving to still greater depths, we propose, once we are carrying out various experiments, to extend at least some of them to greater pressures, perhaps to about 1350 fsw. The work would then not have to be repeated in the future when the depth goal is extended.

H. Possible Use of Hydrogen as an Oxygen Diluent at High Pressures

At depths greater than about 600 fsw, even helium-oxygen mixtures become too dense for comfortable breathing. It has therefore been suggested that hydrogen be partially or entirely

substituted for helium at these pressures. The density of hydrogen is only about half that of helium. Limited tests on primates conducted to date by Dr. Ralph W. Brauer, now of the Wrightsville, North Carolina, Marine Biomedical Laboratory of Duke University, indicate that hydrogen is probably not toxic at depths to about 1500 feet. A. Zetterstrom [61, 62] a Swedish diver, made some dives to 525 feet in which he breathed hydrogen-oxygen mixtures with no apparent bad effects.

The problem with using hydrogen as a diluent for oxygen is twofold: how to produce the mixture without risk of explosion, and how to prevent the possibility of fire or explosion while the diver is in the hydrogen-oxygen atmosphere. These problems are much simpler at high pressures than at low pressures, as can be seen from the following:

At 1000 fsw the total pressure is 31.3 atm. abs. If the diver could breathe satisfactorily when the partial pressure of oxygen is only 0.21 atm, there would be only 0.67% oxygen. To avoid the toxic effects of oxygen, the diver probably cannot work in an atmosphere which has more than 1.5 atm. partial pressure of oxygen; at this pressure, the gas mixture would contain about 4.8% oxygen.

The "upper" flammability limit of hydrogen-oxygen mixtures is not known with certainty, but is probably about 4% oxygen. Thus it appears that safe conditions in which divers may work to at least 1000 feet can be found.

Many measurements have been made of the explosive or flammability limits of hydrogen-oxygen mixtures at one atmosphere pressure, but we have found only one experimental value for the "upper" flammability limit in the pressure region between 600 and 1350 fsw, i.e., the limit for conditions in which the hydrogen concentration is high and the oxygen concentration is low. This one value is somewhat uncertain.

For a pressure of one atmosphere, the upper limit is given in the literature [20] as 95.8% hydrogen and 4.2% oxygen. As the pressure increases, the limits of flammability may tend to widen; at 1350 fsw, e.g., the limiting oxygen concentration may be 4.0% oxygen or less.

We plan to:

(a) Determine the explosion limit for oxygen in dry and moist hydrogen as a function of pressure to about 1500 feet of sea water by use of a spark and/or hot wire as a stimulant.

(b) Carry out measurements to determine the effect of helium on the explosion limit of hydrogen-oxygen mixtures as a function of both helium percentage and total pressure.

(c) Investigate the combustion of paper and other flammables in a non-explosive mixture of hydrogen and oxygen.

J. Miscellaneous Items

In the body of this report there are a number of places in which unfinished projects are mentioned. It is planned to complete the work on these projects if they seem to be of importance.

IV. SURVEY OF THE LITERATURE

There is vast literature on flame retardant treatments and materials, on tests for flame resistance, and on the general problems of fire hazards in confined spaces. An effort has been made to select, from this large number of publications, the ones that are of greatest interest in connection with this project. The selected papers are summarized and/or reviewed below.

Numbers in brackets refer to the list of references. Also enclosed in brackets are our comments on the articles. Thus our comments can be distinguished from the material in the article being reviewed.

The expression "the authors" always refers to the authors of the paper being reviewed, not to us, i.e., not to the writers of this report to the Navy.

A. The Roth Review [48]:

This is a 119-page paper with 256 references, published in 1964. Although it was originally written for use in connection with space-cabin atmospheres, many of the problems discussed are the same as those encountered in diving-decompression chambers. Following are some of the points covered by Roth. Page numbers refer to Roth's review.

p. 2. Ignition sources may be categorized as follows:

(a) Electrical. Electrostatic sparks; frictional or impact sparks; sparks or arcs caused by interrupting the flow of electric currents.

(b) Hot surfaces. Heating by high shear rates; heating of wires by electricity; incandescent carbon-wear particles from electric motor brushes; friction.

(c) Hot gases. Gas flames and shock waves; adiabatic compression.

p. 4. To a large extent generation of electrostatic sparks may be avoided by (1) having as many as possible of the materials electrically conducting and (2) keeping the humidity high.

p. 9. The lower the pressure, the greater is the energy requirement for ignition in a homogeneous gas mixture of fuel and oxygen-containing gas. The same is usually true (p. 16) for the ignition of solids in an oxygen-containing gas mixture.

p. 16. An increase in ambient pressure usually decreases the temperature required for ignition.

p. 18. Addition of an inert gas, such as helium or nitrogen, to a homogeneous fuel-oxygen mixture acts to slow down the reaction in at least two ways: (1) by promoting reaction-chain termination, and (2) by promoting the formation of free radicals which do not lead to branching-chain reaction propagation. This may be illustrated for the case in which the fuel gas is hydrogen, by the following two reactions. M represents a molecule of any inert or other gas:

$$(1)\quad H + OH + M \rightarrow HOH + M$$

$$(2)\quad H + O_2 + M \rightarrow HO_2 + M$$

In reaction (1), two active species are removed to give inactive water molecules. In (2), a hydrogen atom, which can lead to a branching chain by the reaction $H + O_2 \rightarrow OH + O_2$, is removed to form the hydrogen superoxide (perhydroxyl) radical, which usually does not lead to chain branching.

p. 23. As the proportion of oxygen in the atmosphere increases under any fixed nitrogen partial pressure, the burning rate of cloth increases, and at any fixed partial pressure of oxygen, the burning rate decreases with increasing nitrogen pressure.

p. 25. Helium as an oxygen diluent behaves very much like nitrogen in controlling burning rate; it appears that helium dilution offers no great advantage over nitrogen dilution with respect to the fire hazard of burning fabrics. Helium has a molar thermal conductivity about 6 times as great as that of nitrogen. The molar specific heat of helium is 5 cal/mole and that of nitrogen 7.2 cal/mole. Therefore it appears that the relative reaction-slowing effect of inert gases can be related much more closely to their respective molar specific heats than to their molar thermal conductivities. "It is obvious, however, that diffusion and other factors play a role." The high thermal conductivity of helium does, however, tend to lower the temperature of any hot spots present in a chamber, thus

reducing somewhat the danger that ignition will occur.

[The thermal conductivity of the gases at 1 atm. pressure at 300°K (not given by Roth) is:

Helium, 1.51 milliwatts/cm°K

Nitrogen, 0.26

The ratio = 5.8]

p. 26. Coleman [16] measured the rates of combustion in air (at atmospheric pressure) enriched with oxygen, of khaki cotton drill, wool cloth, and a few other fabrics. Except in the case of blue Melton wool and a wool-Terylene mixtures, the rate of combustion always increased quite rapidly as the percentage of oxygen was increased, the pressure being kept constant at 1 atm abs. In the case of the blue Melton wool and the wool-Terylene mixture, the rate of combustion did start to climb rapidly after a concentration of 40 mole-% oxygen was reached. Polyvinyl chloride-coated fabric did not burn in air, but did burn in 26% oxygen.

Coleman also explored the effect of treating white cotton drill with a number of chemical flame retardants. The best of the retardants was effective up to 34% oxygen, but had the disadvantage of being leached out of the fabric during washing. This retardant consisted of a mixture of 30% boric acid and 70% borax applied so that when dry it constituted 10% of the original weight of the cotton drill.

p. 31. Although the combustion of low-molecular weight hydrocarbons, such as methane, will probably never be a factor in diving chambers, the relative effect of inert gases on the burning rate of hydrocarbons is of interest for comparison with the effect on the burning rate of solids.

Clingman and Pease [15] found that in a 10% mixture of methane with various diluents, the relative burning velocities were 0.28:1.0:1.86 when the diluents were nitrogen, argon, and helium, respectively. "Clingman and Pease concluded that these ratios indicated that thermal conductivity factors and diffusion factors are most critical in determining burning velocity.

Morgan and Kane [43] studied the effects of varying concentrations of nitrogen, argon, and helium diluents on the flame speed and flame temperature of propane-, methane-, acetylene-, and hydrogen-oxygen mixtures issuing from a burner nozzle. In all cases, the flame speeds were highest when the diluent was helium, lowest for nitrogen, and in between for argon. Mixtures containing nitrogen had lower flame temperatures than those

containing argon or helium.

p. 32. For diluted methane-oxygen mixtures, the minimum energy to product spark ignition is much greater when helium is the diluent, next greatest for nitrogen, and least for argon. In this respect, helium is more effective than nitrogen in the reduction of fire potential.

p. 16. An increase in the ambient pressure usually widens the flammable range in a homogeneous fuel gas-oxygen (e.g. H_2-O_2) mixture. The same is true of an increase in the initial temperature. [These items are of interest in connection with the possible use of hydrogen as a diluent for oxygen at depths greater than 600 fsw.]

p. 32. The upper limits of flammability for hydrogen-oxygen-inert gas mixtures at atmospheric pressure, the ratio of inert gas to oxygen being 79:21, are 74.6% hydrogen when the inert gas is nitrogen, and 75.7% H_2 when the inert gas is helium; hence for this purpose, helium and hydrogen are about equivalent. However, the minimum spark energy required to set off mixtures of hydrogen and oxygen was 0.043 mJ for helium, but only 0.019 mJ for nitrogen as a diluent, the ration of diluent to oxygen being 79:21.

p. 39. Insulated wires. A number of insulated electrical wires were tested by Klein. The best were as follows:

Type	Gage	Insulation
MIL-C-25038	16	asbestos
MIL-W-7139	20	glass and Teflon
MIL-W-16878	20	Teflon

p. 43. Teflon decomposes very slightly at 400°F; the decomposition rate becomes appreciable at temperatures well above 500°F. The main decomposition product of TFE (tetrafluoroethylene) Teflon is monomeric tetrafluoroethylene. Up to 750°F the main byproducts are fluorocarbon gases varying in chain length from C_3 to C_5. These products are of low toxicity. At temperatures of 759°F and above, small amounts of hydrogen fluoride and perfluoroisobutylene are produced; these are both toxic. Free fluorine has never been found among the thermal decomposition products of Teflon. The ultimate combustion products of Teflon are primarily carbon dioxide, carbon tetrafluoride, and small quantities of hydrogen fluoride.

p. 45. The pyrolysis products of Teflon heated to a temperature of 482°F. or above have been found to be lethal to some rats after a four-hour exposure.

p. 44. Inhalation of the pyrolysis products of Teflon produces in humans a syndrome similar to that of influenza; in the case of persons exposed to the fumes in connection with Teflon resin-processing operations, the symptoms disappeared without treatment or apparent aftereffects 1 to 2 days after exposure. [The case could be much worse for divers trapped in a chamber in which Teflon is heated to very high temperatures. However, if suitable precautions are taken, there would seem to be no danger that a very high temperature would be generated in a diving chamber.]

p. 45. Pyrolysis products of silicone insulation. The toxicity of the pyrolysis products of silicone rubber appears to be about the same as Teflon.

p. 78. Roth lists the following qualifications to be considered in choosing materials for use in space cabins:

1. Lowest potential as an ignition source
2. Highest ignition temperature
3. Lowest rate of combustion
4. Lowest explosion potential
5. Lowest potential as a source of toxic combustion products

Possibly hazardous items are:

1. Communication equipment
2. Electrical wiring
3. Air-circulating and filtering equipment
4. Temperature-regulating equipment
5. Furniture
6. Clothing
7. Food and food-preparation equipment
8. Entertainment equipment
9. Waste-disposal equipment
10. Housekeeping equipment
11. First-aid kit

p. 79. Magnesium metal burns in high-oxygen environments under some conditions. Ignition of magnesium by friction can occur.

For electrical insulation, "it would appear that basic glass-fiber or asbestos insulation with silicone or fluoroplastic binders would be safest. Polyvinyl chlorides should be avoided."

p. 81. Electric and electronic equipment should be made explosion proof.

p. 82. To prevent sparking or arcing, the following should be used: capacitors across potential arc points; abrasion-resistant electric wiring, or enclosure in conduits; proper support of electric wiring; proper grounding.

p. 87. For chambers in which persons are to spend the night, it may be a good idea to install an infrared or ultraviolet type of flame detector.

p. 91. In case of fire, the use of towels for snuffing out the flame should in general be discouraged, expecially in oxygen-rich atmospheres. The fabric of which the towel is made may be fire-resistant in air, but will probably burn in an oxygen-rich atmosphere.

In another paper Roth [48] gives a good discussion of the problem of choosing the best space-cabin atmosphere. "In the past, selection has been primarily on engineering grounds." The physiological and the fire problems are both described.

B. Harter [28]: The Fatal Fire in the U.S. Navy Experimental Diving Unit, and Other Items.

On 22 March, 1945, a fire occurred in a recompression chamber aboard a Navy diving ship. Two men subsequently died and another was severely burned. The chamber was at a depth of 40 feet and the subjects were breathing from oxygen inhalators. This fire led to a number of improvements in the outfitting of Navy diving chambers. Nevertheless, on 16 February, 1965, a fire occurred in a hyperbaric research chamber at the U.S. Experimental Diving Unit, Washington, D.C., with the resultant loss of the lives of two Navy divers. This fire led to the adoption of still further precautions, and to a request that a research contract on fire prevention be negotiated by the Navy. [The resultant contract is the one which forms the subject of this report.]

Harter's paper gives the details of the circumstances surrounding the 1965 fire in the hope that "those who read it will benefit from" the Navy experience.

At the time of the fire, the divers were at a pressure of 41.4 psia (60 fsw), in an atmosphere with the approximate composition 27% (by volume) oxygen, 36.5% nitrogen and 36.5% helium. A portable carbon dioxide scrubber was in operation; it served the dual purpose of removing carbon dioxide and of obtaining homogeneity of the gas [illegible] in the chamber. One minute and 10 seconds before the f[illegible] 5 cu. ft. of oxygen was admitted to the chamber over a 5-minute period. The point of introduction of the oxygen was near the scrubber to provide rapid mixing of the oxygen with the existing atmosphere.

After the accident, the Investigating Board determined that the fire was initiated by a localized heat source in the scrubber motor. Overheating of the motor was caused by faulty operation of the centrifugal throw-out switch, which resulted in the motor running on the starter windings.

Among the items that burned in the fire were: cotton terry cloth robes; cotton mattresses; fabric-covered ducts (part of the air condition system); rubber insulation on a cable; a rubber cord; eight oxygen inhalators, together with corrugated rubber tubing with stockingnet covering, the packing in a stuffing tube for the air conditioning sensing element, plastic inserts in a gas pressure regulator, reading material, toilet paper, and the paper filter elements in the scrubber. The filter elements were impregnated with a phenolformaldehyde resin and a kerosene-like liquid. This latter played an important role in getting the fire started when the motor overheated.

The interior of the chamber was coated with white paint. This did not burn during the fire, in spite of the high temperature that developed. Four air-conditioning fan motors in the chamber were UL approved and explosion proof. These four motors were not damaged by the fire. On the other hand, the scrubber motor, which apparently started the fire, was not manufactured to explosion-proof standards.

While Navy fire-retardant paints were found to burn when placed on thin sheet metal, they could not be ignited on the chamber walls in air at atmospheric pressure, even when a butane torch flame was applied to the surface. The reason for this is that the heat from the torch is rapidly conducted away from the source by the 2-1/2-inch-thick steel plate, thereby preventing the paint from reaching ignition temperature.

In the ideal pressure chamber there would be no fire hazard if the following could be done:

1. Eliminate all sources of ignition.

2. Eliminate all flammable materials.

Since it is impossible to carry out these two items completely, two others are suggested to mitigate the fire hazard:

3. Provide adequate fire extinguishing facilities.

4. Utilize the lowest partial pressure of oxygen (at any given time) that the work in the chamber permits.

Harter then outlines the steps taken to prevent fires in the future, inside the Navy Experimental Diving Unit chambers. Among many others, the following are mentioned:

1. Use of "Fluorolube" when a lubricant is needed.

2. Use of fiber glass mattresses.

Harter suggests that when portable high-pressure water cylinders become available, they should be installed in the chamber as part of the fire-fighting equipment.

The paper outlines development work that should be done to promote safety in hyperbaric chambers. The paper al reports some experimental results obtained at the Naval Research Laboratory (NRL). These results have now been reported independently by NRL [32]. Harter's paper also mentions the early work done by the Linde Research Laboratory, in which apparent sharp maxima were found in several curves for burn rate vs. pressure. Harter rightly states that these were preliminary results and were, at that time, unconfirmed. [Subsequent extensive experimentation has shown that these apparent maxima were not real, but were due to random error in the early results. When enough tests are made, the burning curves turn out to be smooth.]

C. Royal Air Force Institute of Aviation Medicine

Denison, Ernsting, and Cresswell describe, in two reports, experiments conducted with a lifesize brass mannequin and with dead pigs, and in a third report, Denison reviews the risks in using 99% oxygen.

Report No. 320 [22]. A brass life-size mannequin was coated with a 1 mm thick layer of PVC (which has thermal properties similar to those of the human skin) and clothed in denim overalls. (The report does not state whether the denim is cotton or wool.) The dummy was placed in a chamber filled with pure oxygen at a pressure of 1 atm., and the overalls were ignited electrically. Five seconds after ignition the overhead sprinklers were turned on. The results were:

(1) Immediately upon ignition a 5 cm wide front of flame flashed over the entire surface of the overall, leaving it virtually unscathed, but flaming at all its edges and at many small points on its surface.

(2) For the next two seconds these separate fires remained small, then, over a further two seconds, they rapidly enlarged and coalesced into a 6 ft. column of fire.

(3) This fire persisted for about 30 sec. after operation of the sprinkler system.

(4) The dummy's skin and overalls were almost completely destroyed, small areas of unashed overall and coating remaining about the head and shoulders.

These results demonstrated what would have been a fatal fire, had a man been in the chamber. After this preliminary test, a series of 45 experiments upon the effects of igniting clothing, either on the dummy or on dead pigs, were carried out in 6 different gaseous environments as follows:

Partial Pressure, atm.		Total Pressure, atm.
O_2	N_2	
1	0	1
0.75	0.25	1
0.50	0.50	1
0.21	0.79	1
0.33	0	0.33
0.25	0.25	0.50

The experiments were carried out in a rectangular steel compartment (measuring 8 x 8 x 12 feet) that was stripped of all equipment not used in the tests.

It was found that the damage to a man is critically dependent upon the type, fit, and flame-proofing of his clothing and on the timing, density and distribution of the extinguishing water spray. The danger is particularly aggravated by the presence of nap or body hair, which explosively propagates the fire across the surfaces of clothing and of experimental subjects.

The experiments led to the following four recommendations:

(1) Occupants should wear a tight fitting single-layered garment of light weight open-meshed material, proofed with a 10% pick-up of borax/boric acid. This overall should conform as closely as possible to the body to avoid creating tracks for the spread of a flash fire. Note from p. 4 of the report: "borax/boric acid treatment is ... temporary and is damaging to the fabric."

(2) The extinguisher system should provide water spray of at least 5 ml/min/cm² throughout the envelope of the occupants' movements, within 2 seconds of operation.

(3) The extinguisher system should be automated to respond to a flash fire within that envelope, and should have a manual override that can be operated from the inside and the outside of the chamber.

(4) A hand-operated hose should be provided, to be used to douse those areas, such as the crotch, that are shaded from the general spray.

Report No. 343 [22]

This report covers experiments carried out in a chamber having a volume of 4,500 liters, in a number of additional atmospheres. The new work was on a much smaller scale than that described in Report No. 320. In the new work, tests were made (1) on 15 cm. square samples of washed denim (the paper does not say whether this is cotton or wool) and (2) on the legs or flanks of undepilated dead pigs, each member being dressed in a washed denim sleeve. The only indication of whether the samples were held horizontally or vertically during the tests is that they were "weighted"; thus the samples were probably held in the vertical position. The samples were ignited by passing a 5-ampere current through a 30-cm. length of nichrome wire (resistance 5 ohms) sewn into the material.

The weighted squares and the sleeves and pig members were suspended above a bath of water. After 10 sec. for the squares and 15 sec. for the pig members, the support was removed and the sample allowed to fall into the water. The areas of burnt clothing and skin were then measured. Table 4 gives (1) the time (seconds) elapsed between the turning on of the electrical power and ignition, and (2) the areas burned in 10 seconds for the squares and in 15 seconds for the denim sleeves and the pig-member skins.

The fact that the denim did not ignite at all in air at 1 atm. indicates that perhaps it was wool rather than cotton.

As seen in Table 4, the rate of flame spread increased with increase of air pressure.

Even at 5 atm. air pressure, there was no flash propagation of the nap of the denim or by the hair of the pigskin. However, in pure oxygen at the same partial pressure, there was almost explosive propagation of fire.

Report No. N66-29324 [21]

In this report, Denison assesses the risk in using 99% oxygen in a chamber to be occupied by human beings.

p. 2. P. Voigtsberger in Germany found that "the spark energies required to ignite common clothing materials may be decreased more than one thousandfold in pure oxygen to levels similar to those of electrostatic sparks."

The main principles of reducing the fire risks in pure oxygen are: (1) reducing the number of ignition sources to a minimum, (2) reducing the quantity of flammables to a minimum, (3) separating potential ignition sources and flammables as widely as possible, (4) having an effective means of extinguishing fires, (5) having a clearly understood set of safety regulations, and (6) having a simple and clearly understood fire drill.

p. 8. Certain materials, such as nylon, melt when heated, forming adherent hot masses which produce severe local burning.

It is proposed that persons wear (1) pocketless one-piece overalls with short sleeves and 3/4 length trousers to reduce the likelihood of contact with potential ignition sources and (2) canvas gym-shoes with conducting rubber soles.

The best sealing material is probably Viton.

pp. 9-10. If an adsorbent for environmental contaminants is to be used, it is recommended that Molecular Sieves be tried, since they are completely non-combustible.

D. Hospital of the Good Samaritan, Los Angeles

The 1966 Paper [51]. The only tests of hyperbaric fire hazards that have been reported on life-size mannequins, are, so far as we know, those at the Royal Air Force Institute of Aviation Medicine (summarized above), and those conducted at the Hospital of the Good Samaritan in Los Angeles.

The Los Angeles experiments were carried out in a hyperbaric chamber 26 ft. long by 10 ft. in diameter, at air pressures of 45 psig (= 60 psia). It was found that it took as long as 25 seconds to completely extinguish clothing fires on mannequins by water spray from an overhead system because water did not

reach all the burning areas, expecially underwear, fast enough to put out the fires sooner. A fire of the same magnitude involving the same garments was totally extinguished in about 2 seconds by direct attack with a hand-operated water line.

In two tests, a skilled operator attempted without success to extinguish clothing fires on a mannequin with a fire blanket.

The authors of the 1966 paper recommend the following:

(1) The chamber should be equipped with a fixed water-spray system that will supply water rapidly at a pressure greater than the highest gas pressure to be used in the chamber. The fixed system should be operable by quick-opening valves both inside and outside the chamber. The feasibility of automatic actuation by means of fire-responsive devices should also be considered. If this were deemed undesirable under certain conditions--for example, during surgery--the system could be designed to permit disconnection of the automatic response, as long as manual operation remained available. [We wonder whether the possibility of using a fog nozzle instead of a spray nozzle has been considered by the authors.]

(2) There should be one or more flexible hand-operated water lines, each with a spray nozzle and quick-opening valve. The authors of the paper believe that in addition to the flexible line, a fixed system is absolutely essential to take care of the remote possibility that the chamber occupants will be incapacitated for some unforeseeable reason, or that they will panic, or that nobody will take proper action to handle the emergency. There must be a way for attendants outside to take action; this would be done by use of a fixed system.

(3) Occupants of the chamber should wear flame-retardant coveralls or jump suits.

(4) Personnel assigned to hyperbaric chamber duty must be thoroughly trained in all pertinent aspects of fire safety. They must be made familiar with all the fire-fighting equipment and its operation and use. They must be alert to fire dangers and prepared to react quickly and effectively in the event of a fire emergency.

The 1965 Paper [55]. Page 269. A pressure of 105 psia is the highest contemplated for hospital hyperbaric chambers. The usual pressures are 30 or 45 psia.

In considering the fire safety aspects of hyperbaric chambers, one factor is of overriding importance. Patients and medical personnel are trapped in an environment from which quick escape is

impossible once they have entered the chamber, the doors have been closed, and the air pressure raised. If a person has to leave the chamber, there are only two possibilities; either (1) he must be depressurized - and depressurized slowly, in order to avoid the dangerous and possibly fatal physical effect known as "the bends." Even if the chamber were depressurized at a rate of 2 psi/min., which is considered a rapid rate, any fire occurring inside must be controlled and extinguished long before evacuation becomes possible; [or (2) an adjacent chamber or lock, kept at the same pressure as the main chamber, must be provided. The second alternative will be useful only if the fire can be kept from spreading to the second chamber if the door is opened.]

p. 272. In experiments on extinguishing fires in hyperbaric chambers with sprays of water, it was found that the resistance offered by the denser-than-normal atmosphere impeded the falling water droplets to a significant extent. As a result, the system was redesigned with more nozzles to ensure adequate coverage of the entire chamber area under all operating conditions.

pp. 273-277. Burning tests made on methenamine tablets and on strips of cotton batten vertically and at an angle of 45° in air at pressures of 1, 2, 3, and 4 atm. abs., showed that the rate of combustion increased with increase in pressure in all cases. Another interesting observation was made: although the rate of combustion always increased (at 45° and 90° angles) with increasing air pressure, the "efficiency" of combustion decreased as the pressure was increased. The reduction in burning efficiency was evidenced by the increasing amounts of carbon char that remained after burning of the methenamine tablets, and by yellower flames and greater amounts of black smoke in other tests. The ignition source for all experiments was a propane flame, which became smoky as the air pressure was increased.

E. Flame-Resistance of Fabrics

The article by Coleman [16] has already been abstracted as part of the report on Roth's review (above). An article by Cook, Meierer, and Shields [18] covers a part of the material presented in later sections of this report.

Yockers [60] has reported on some common fabrics. "Among natural fibers used to make clothing fabrics, wool is by far the least combustible. Silk in its natural state also is not very combustible, but in many silk fabrics, foreign materials are added" which "very often increase the combustibility considerably." Of synthetic fabrics, "Saran, Verel, Vinyon, and Dynel are quite flame resistant. The following burn: Acetate, Fortisan, Orlon, Acrilan, Vicara, and Dacron, but none of these will burn as fast as cotton or rayon."

Napped cotton and rayon are dangerous because flames will race across the brushed surface at an incredible rate of speed. A flame will not flash across the nap on any of the present synthetic fibers because the nap softens or melts.

In a project [40] carried out in the laboratories of the National Bureau of Standards in Washington, but not by the NBS staff, over 100 different samples representative of materials in current use in commercial airplanes were tested in air at atmospheric pressure by various standard test methods. "Future work on the project will include toxic gas analyses on the combustion products and also full-scale cabin fire tests, using interiors with different degrees of fire resistance." Results "will be covered in separate reports." A description of the fabrics tested, and the results of the flammability tests, are tabulated separately, but the manufacturers or vendors of the materials are not given.

Some of the comments and conclusions in the report are: "Plastics in general produce much larger quantities of smoke than do the cellulose-derived materials," and when heated and/or burned they sometimes produce toxic gases other than carbon monoxide.

Materials are classified with respect to their ability to resist fire, in the following order: (1) fireproof, (2) fire resistant, (3) flame resistant, and (4) flash resistant. Fireproof and fire-resistant materials are generally limited to the metals, fiber glass, and asbestos.

Results of the standard tests, carried out in air at atmospheric pressure, were:

Horizontal test: Vinyl-coated Fiberglas or Dynel fabrics did not show any appreciable burning. Neoprene sponge burned rapidly.

Vertical test: All four of the vinyl-coated Dynel fabrics tested showed zero flaming time.* Eleven vinyl-coated Fiberglas fabrics were self-extinguishing within half a minute. The most flammable fabrics were the vinyl-coated cotton materials.

Radiant Panel test: This was the most severe of the three tests. The best results were obtained with vinyl-coated Dynel and with sheer, uncoated Dacron fabrics. "The Dynel fabrics apparently owe much of their exceptionally low flame-spread index to the tendency of the material to shrivel up and pull away from the flame or heat."

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*Flaming time = time elapsed after ignition flame is withdrawn until sample flame extinguishes itself.

Reflectivity increased the flame resistance. Of two Mylar sheets, identical except that one was aluminized, the aluminized one had the greater flame resistance.

Nylons melted and dripped when tested by this method.

The following conclusions were reached with respect to the test methods: (1) Burn rate by the vertical test method was of the order of 10 times more rapid than that by the horizontal test method, with comparative increase in burn length. (2) Self-extinguishing time was about the same in these two test methods. (3) The vertical test method is somewhat more severe than the horizontal test method in that fewer materials were self-extinguishing. A burn length of 12 inches by the vertical test method was roughly equivalent to a burn length of 1.5 inches by the horizontal test method. (4) The radiant panel method was the most severe of those used, and was the only one that yielded ratings which took into account the heat generated by the burning sample and the smoke produced.

A program [34] is currently under way at the Bureau of Mines laboratory in Pittsburgh "to determine the ignition and combustion characteristics in hyperbaric atmospheres of a variety of combustible materials. The work was undertaken at the request of the Compressed Gas Association....and is being supported by the U.S. Public Health Service. Among measurements to be made are: (1) minimum ignition temperatures in a heated vessel and by the hot plate method; (2) burning rates with the samples at an angle of 45°, and occasionally in the horizontal and vertical positions for comparison purposes; minimum electrostatic spark ignition energy. Circulation of the quarterly reports on this contract is restricted; however, the first one contains very few experimental results, since most of the time was spent in planning the work and in building or arranging equipment.

[Of great interest in this project will be the work on minimum static spark ignition energy.]

F. Tests in 100% Oxygen and in Oxygen-Rich Gas Mixtures

Huggett and his associates [31] determined the flammability of various materials in 100% oxygen at a total pressure of 258 mm Hg (5 psia).

The combustion chamber was a cylindrical pressure vessel 14.5 inches in diameter by 33 inches long, with a volume of 3.2 cu. ft. (90 liters). The vessel had 8 viewing ports. Ignition temperatures were not measured. For measuring burn rates, samples

were ignited by means of an electrically heated Nichrome resistance wire. For measuring the energy concentration (calories/cm^2) required to bring about ignition, radiant heat was supplied by a 1200-watt projection lamp. The radiant energy was focused by two ellipsoidal mirrors, and was measured by means of a heat flux transducer.

The samples were 1/2 inch by 3 inches long and were held either horizontally or vertically. In the latter case, they were always ignited at the top, and no consistent difference was found in the burning rates measured in these two positions.

The authors conclude that flame spread rates over the surfaces of materials are greater by one to 3 orders of magnitude in oxygen at 5 psia than in air at atmospheric pressure. Some materials which do not burn at all in air burned vigorously in 5 psia oxygen. Prolonged storage in oxygen has no appreciable effect on flame spread rate.

No major differences were found in the energies required for ignition of materials in air, in oxygen, or after storage in oxygen. Normal fire-retardant treatments for fabrics were not effective in the oxygen atmosphere.

This paper gives an extended qualitative discussion of the theory of the combustion of solids.

p. 6. In one experiment, "multiple layers of Scotch tape were pasted on an aluminum plate one-eighth of an inch thick. A 5-ply layer of Scotch tape was found to be not ignitible in 258 mm O_2; a 6-ply layer did ignite and burn, but the burning rate was only about one-half that obtained with a 20-ply layer." This experiment helps to explain why even a flammable coat of paint on a steel surface cannot be ignited, because the steel carries off the heat too fast to permit the paint to reach ignition temperature [28].

p. 19. The following materials were found not to ignite in pure oxygen at 5 psia pressure: Kel-F, Teflon, glass wool, and a number of samples of wire insulation, identified as MIL W 16878 green, black, yellow, and white. Materials which ignited but had a low rate of flame spread in the horizontal position were:

PVC	0.10 inch/sec.
Silicone rubber	0.14
Viton A	0.003

In a later report [30], Huggett and his associates repeated some of their previous tests. The new results were, with one

easily explainable exception, in excellent agreement with the earlier ones.

A brief study of combustion in 100% oxygen at a pressure of about 5 psia as compared with combustion in air at atmospheric pressure was made by Hall and Fang [27] at the U.S. Naval School of Aviation Medicine. Samples (0.5 inch wide by 4.5 inches long) of filter paper and of a few fabrics were burned, apparently in the horizontal position (the report does not say).

Findings: "As compared to the control experiment at sea level pressure in air, it was found that paper ignited at a lower temperature and burned approximately six times as fast in the 5 psia oxygen atmosphere. Neoprene-coated nylon twill, light weight nylon, and vinyl plastic all ignited, whereas in the control condition (air) they had not ignited, but melted. A dead rat was merely singed on its exposed side in the control condition, but two dead rats exposed in the 5 psia oxygen atmosphere were burned over their entire bodies. Toweling material used to test its smothering properties burst completely into flame within one-half second of contact with the fire, whereas in the control condition it extinguished burning paper in one-fourth second."

A study is being carried out by Johnson and Woods [32] of the Naval Research Laboratory. "The most profound effect on both ease of ignition and linear burning rate was caused by oxygen enrichment [of air]. For example, many materials which did not ignite in 21% oxygen ignited and burned readily at 31% or 41% oxygen. With a given atmosphere, increase in pressure was often effective in causing ignition where no ignition occurred at lower pressures. Substitution of helium for nitrogen in mixtures with oxygen had two generally significant effects: Helium decreased the tendency of a material to ignite; [this] effect was shown to be due largely to the high thermal conductivity of helium. Once ignited, burning rates were often much faster in helium than [in] nitrogen... Although this study was not exhaustive, only Teflon and glass fabrics were judged to be non-flammable...at 41% oxygen in nitrogen at one atmosphere [pressure]. Of course, many metals and other inorganic materials, such as asbestos, should be suitably non-flammable also."

Another study [25] was carried out at the Dynamic Science Corporation, Monrovia, California. Some of the combustibility properties of polyethylene, PVC, and silicone rubber were evaluated in a cylindrical stainless steel chamber 12 inches in diameter and 18 inches high. The wall temperature of the chamber was controlled from room temperature to 1650°F. The sample (5 to 6 g. of the cast material) was placed on a tray equipped with a separate heater. The autogenous ignition temperature of PVC was

found to decrease as the partial pressure of oxygen increased, from 514°C at 155 mm partial pressure of oxygen, to 390°C at 760 mm oxygen, regardless of whether the ambient gas was 60% O_2 - 40% N_2, 60% O_2 - 40% He, or 100% oxygen. It was found that, prior to ignition, there was an exothermic surface reaction which caused the measured sample temperature to become 60° to 70°C higher than the tray temperature.

The burning time of the 5.5-gram PVC varied from about 200 seconds at an O_2 partial pressure of 15 psia to 900 seconds at 3 psia O_2, regardless of dilution.

Ignition of silicone rubber began with a brilliant yellow flame. After the flame went out, the sample continued to glow for 1 to 5 minutes.

The spontaneous ignition temperature was a little over 500°C. However, at 200°C an oil evolved from the sample. This apparently volatile silicone condensed on the cool view window and oxidized as the heat increased. The reaction left a heavy, white film on the window and a suspension of fine silica in the chamber. The suspended particles which formed prior to ignition and obstructed the visual observations could create similar problems in actual spacecraft operations. For example, the following difficulties could arise:

1. Visual interference
2. Fouling of the filter system
3. Deposition of residue throughout the system

The burning time of the silicone rubber varied from about 80 sec. at P_{O_2} = 15 psia to 300 sec. at P_{O_2} = 3 psia, regardless of whether the ambient gas was 100% or 60% O_2.

It was found that polyethylene could not be ignited at any P_{O_2} below 180 mm and PVC not below P_{O_2} 155 mm. The P_{O_2} limit for silicone rubber was found to be below 155 mm, but was not determinded more exactly.

G. The Relative Effect of Diluent Nitrogen, Helium, and Argon

An article [19] on this subject by Cook, Meierer, Shields, and Nevins covers part of the material presented in later sections of this report.

Huggett and his associates [30] extended their work to include tests in oxygen-nitrogen and oxygen-helium mixtures as well as in pure oxygen. As detailed below, they were able to correlate

their results with the combined heat capacity (per mole of contained oxygen) of the gases in a mixture, and they made a start toward arriving at a mathematical model for the combustion of solids in mixtures of gases. The apparatus and technique were the same as described above for their earlier work.

The gas mixtures and pressures used were:

Composition, Mole-%	Pressures, psia			
	O_2	He	N_2	Total
80% He - 20% O_2	2.94	11.76	0	14.70
54% He - 46% O_2	3.38	3.97	0	7.35
30% He - 70% O_2	3.5	1.5	0	5.0
54% N_2 - 46% O_2	3.38	0	3.97	7.35
30% N_2 - 70% O_2	3.5	0	1.5	5.0
100% O_2	5.0	0	0	5.0

"There is an inherent variability in the combustion process and some scatter in the data is to be expected."

It was found that, with the samples in the horizontal position, there was no increase in burn rate with increase of pressure. [This confirms results obtained by us and reported in a later section.]

A reasonably consistent linear correlation of burn rate with one of the physical properties of the gases was obtained by plotting the rates of flame spread for a given material against the logarithm of the heat capacity of the gas mixtures per mole of oxygen. The straight lines thus obtained were extrapolated to zero burn rate. For any of the gas mixtures and pressures listed above, there could be defined, in terms of heat capacities per mole of oxygen, a gas composition such that the atmosphere would no longer support combustion.

The authors derived a simplified mathematical model of the burn rate mechanism. In this model, diffusion and heat conduction are considered to be the rate-controlling processes; this consideration eliminates chemical reaction rates from the model. All parameters are independent of pressure, and the model therefore applies, in general, only to combustion propagation in the horizontal position or <u>downward</u> in other positions; there is a possibility that it may also apply to upward combustion in zero gravity.

The model "states correctly that the flame-spread rate is inversely proportional to the thickness of a cast sheet of sample."

The model cannot, however, be used to predict either the absolute burning rates or the effect of gas composition. Nevertheless, the model represents, as does the one given by Williams [58, pp. 202-215], a good start on a difficult problem.

From the model given by Huggett et al., it would apear "that polyatomic gases would be more effective in reducing flame spread rates than monatomic or diatomic gases because of their higher volumetric heat capacities. A gas such as CF_4 shcuild be highly effective in preventing flame propagation. Physiological activity and high density, however, might prevent its use in life support systems."

In spite of the good correlation obtained between burn rates and heat capacities, Huggett et al., conclude "that the much larger flame spread rate in helium-oxygen atmospheres as compared to nitrogen-oxygen atmospheres is attributable primarily to the higher thermal conductivities and presumably also higher diffusivities of the helium mixtures, and only secondarily to the higher flame temperatures associated with the lower heat capacity of helium."

[Thus it would appear that the heat capacity correlation may be of interest only in defining the region of non-combustion.]

Chianta and Stoll have published two reports. In the first one [11], comparative burning rates in the horizontal position were measured for square samples, 9.5 cm. on edge, of 3 cloth fabrics: 5 oz/yd^2 cotton used to make Navy issue pajamas, 2.5 oz/yd^2 cotton sheeting, and 3.0 oz/yd^2 of Nomex cloth. Experiments were conducted inside a vessel (neither dimensions nor material of construction are given) at total pressures varying from 4.6 to 14.7 psia, with mixtures of oxygen and nitrogen varying from 20 to 100% oxygen in steps of 10%. A few tests were made with a mixture of 40% O_2 with 60% argon. The source of heating and ignition was a Nichrome resistance wire.

Results were determined by watching through a glass window.

The following applies to the O_2-N_2 mixtures:

Three points in the heating and burning of the samples were observed and marked on the record: the "scorch" point, i.e.. the time of the first sign of scorching; the "flame" point, i.e., the time at which flaming occurred; and "flameout", i.e., the time at which the flame extinguished, often due to complete consumption of the specimen.

It is seen in a plot of the results that the scorch point varies relatively little with oxygen concentration but that the

flame point and total destruction are reached far more rapidly as the oxygen content increases. All progressions are smooth and no optima or discontinuities are evident. From these data it appears that no optimum combination of O_2 and N_2 exists.

The authors state that at each pressure, the 5 oz/yd² cotton was destroyed most rapidly, the 2.5 oz/yd² cotton less rapidly, and the Nomex least rapidly. At atmospheric pressure, the rate of combustion of the Nomex represented the following fractions of the rate for the 2.5 oz/yd² cotton cloth:

0.26 at 30% O_2 - 70% N_2

0.39 at 40% O_2 - 60% N_2

0.44 at 50% O_2 - 50% N_2

The relative advantage of Nomex over cotton gradually became less as the percent oxygen increased, although the fraction was still only 0.67 in 100% oxygen. Below 50% oxygen there was no significant difference in the flame temperatures of cotton and of Nomex.

At a total pressure of 4.6 psia, Nomex did not flame at all in the 30% O_2 - 70% N_2 environment, and at 40% it was self-extinguishing. At percentages of oxygen above 50%, however, the Nomex "burst into flames suddenly and burned fiercely when once ignited."

In separate experiments with a mixture of 40% oxygen and 60% argon, Nomex did not catch fire at any total pressure except 7.4 psia, and even here there was a long delay (920 sec. vs. 43 sec. when the diluent was nitrogen). The condition 40% O_2 - 60% argon was considered to be right on the border between combustion and non-combustion. Although the use of argon as a diluent is probably impractical for physiological reasons, it is interesting that Chianta and Stoll found that argon is a slightly more effective flame suppressor than nitrogen under the conditions they tried.

Irrespective of whether nitrogen or argon was used as the diluent gas, the rate of combustion usually reached a maximum at a total pressure of 7.4 psia in the pressure range (4.6 to 14.7 psia) studied.

In a later paper [12], Chianta and Stoll report that key experiments with nitrogen and argon were repeated and the original findings were substantially corroborated.

The data from these experiments revealed that the scorch point varied very little under any condition, while flaming, cessation of flaming, and destruction rate were functions of the mass flow of both oxygen and diluent.

Unfortunately this second paper [12] gives no tables of data, so no calculations can be made on the relative effect of the

diluents under either constant mass ratio or constant volume ratio, diluent:oxygen.

H. History and General Discussion of Fire Hazards and Fire Fighting

Clamann [13] gives a general discussion of the problem of persons in isolated chambers.

Clamann in 1938 was apparently the first to study fire hazards in oxygen-rich atmospheres; he gives a reference to a 1940 paper by himself on the subject. He found, for example, that in an 82% O_2 - 18% inert gas mixture at a total pressure of 4.45 psia, a cigarette and strips of paper burn much faster than in air at atmospheric pressure. The shape of Clamann's curves (his Fig. 70)would be similar to ours if we used the same parameters.

Carbon dioxide must be removed from the atmosphere so as to keep the concentration below the equivalent of 1% to 2% at ground level pressure.

The next paper after the 1940 one on the subject of space cabin atmospheres was, according to Clamann, published in 1959 by Archibald and Simons. Since then, many papers on this subject and on hyperbaric atmospheres have been published.

In another paper [14] Clamann describes some of his early experiments. Burning time of a horizontal strip of paper (45 x 20 mm) was 7 sec. in air at 1 atm. pressure and 3 sec. in 100% oxygen at 2.9 psia, a ratio of 2.3. In air at 2.9 psia, the burning time was 9.5 sec., and at lower pressures, ignition was impossible. Similar results were obtained by Archibald and Simons in 1959 with cloth from burning flight clothing.

"In pure oxygen, burning speed may acquire almost explosive characteristics."

"At ground level pressure at 21% O_2, and almost down to 500 mm Hg at 25% O_2, a 'field' of nonflammability exists for helium mixtures." [This statement anticipates our work on the region of noncombustion.]

For cigarettes in the vertical position, Clamann found that in 100% O_2 the ratio of the burning rates at 14.7 and 5.0 psia was 4.52.

Brown and Smith [8] give some general safety precautions that should be considered in the design and operation of hyperbaric

chambers. They recommend that all in-chamber receptacles and lights should be of the non-sparking, explosion-proof type. They state that the safest policy is to eliminate, whenever possible, all electric motors by substituting air-driven or hydraulic motors. One means of circumventing the hazards from certain electrical motors, such as those used for driving internal air-conditioning fans, is to mount them outside the chamber with pressure-proof Teflon-packed mechanical shafts through the chamber walls, with flexible couplings inside.

"Even when air motors are substituted, they still have to be lubricated and, as in all in-chamber lubrication, one must use non-toxic and noncombustible lubricants." Here, some of the polymers of trifluorovinyl chloride (Fluorolubes)* are expecially useful.

Water is the safest material for use as a fire extinguisher, and the time-honored sand pail should not be forgotten.

In a good summary [7] of fire hazards in hyperbaric chambers, Bond states:

"Of the many hazards associated with operation of hyperbaric chambers, by far the most serious is that of accidental fire."

"Unless special efforts are made to remove all oxygen-rich exhalations of the patient from the chamber, some increase in oxygen concentration is inevitable. This enrichment will augment the possibility of ignition and flame propagation."

"The toxicity of carbon dioxide is in direct proportion to [its] partial pressure." In the absence of a special breathing system to protect against carbon dioxide toxicity, CO_2 extinguishers cannot safely be employed in a hyperbaric chamber.

In a search to replace CO_2 as a gaseous fire-quenching agent, both nitrogen and helium have been considered and tested. At the present time, it appears that neither of these inert gases are of value in fire-fighting [except by the rapid dilution method outlined below], since it is not possible to maintain a significant concentration of the gas in a given location. "On account of their narcotic properties, the gases of heavier molecular weight cannot be considered for such use under pressure."

Every chamber should be equipped with both sand and water buckets to take care of small, localized fires.

Rapid dilution of the chamber atmosphere with an adequate quantity of either helium or nitrogen will reduce the oxygen

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*Hooker Chemical Corporation, Niagara Falls, New York

concentration to a level at which it will no longer support combustion. [This method of fire fighting has the advantages that no harm is done by soaking anything with water or by covering things with sand, but the method requires that the chamber be engineered to provide for almost instant mixing of a large quantity of the diluent gas with the chamber atmosphere. This could be done automatically if a good fire detection system has been provided.]

General suggestions for the safe handling of oxygen and oxygen-enriched atmospheres are given in references [44, 17].

There is a Swedish student dissertation [29] on this subject, but so far no translation has beer made.

J. National Conferences

At least three conferences have been held on the subject of this report within the last few years. They are:

October 2-3, 1962, Textile Flammability Conference, Boston, sponsored jointly by the National Fire Protection Association and the U.S. Public Health Service.

December 2-3, 1966, Conference on Burns and Flame-Retardant Fabrics, New York City, sponsored by four different organizations, including the New York Academy of Medicine, where the meeting was held.

January 17, 1967, Technical Session on Under-Ocean Technology, New York City, sponsored by the Compressed Gas Association.

Of these three, the only one for which the papers have already been published [45] at the time of writing of this report is the 1962 Textile Flammability Conference. Most of the papers are either not of immediate concern to the subject of this report, or present facts which have already been covered in reviewing other papers.

A prepublication copy of one [9] of the papers presented at the 1966 conference referred to above, was supplied to us. The paper describes modacrylic fibers in general and Union Carbide's Dynel in particular. "Available in what is known as staple form, which is similar to cotton or wool in that it has a short fiber length, [Dynel] can be processed to yarns for knitting, weaving, felting, tufting and other textile operations. The fibers, when made into fabrics, produce goods which are warm, soft and generally characterized as having a wool or fur-like hand and appearance. The fibers are dyeable, they are basically chemically inert, and self extinguishing when the source of flame is removed. It is important to note that while burning, the fibers tend to shrink and

contract but do not drip a hot melt, which in some cases can be more of a problem than the burning fabric itself."

One important use for Dynel is in the manufacture of flame-resistant blankets. In air at atmospheric pressure, damage from a burning match or other source of flame dropped on the blanket is confined to the immediate area of the match or other flaming object. [A drawback of Dynel blankets is the easy generation of sparks of static electricity. This drawback may, however, be overcome in the future.]

[Dynel is a copolymer of vinyl chloride (about 60%) with acrylonitrile.]

[A third synthetic copolymer is Rovana, trade name for Dow Chemical Company's saran flat monofilament. Saran is now a generic term for thermoplastic resins obtained by the polymerization of vinylidene chloride with lesser amounts of other compounds. Rovana fabrics are constructed with Saran flat monofilament in the warp, filled with one or more of the following: Verel, rayon, polyester, and flax. For evaluation of fire-retardant Rovana fabrics, see a later section of this report.]

K. The Static Spark Problem

The Bureau of Mines has reported [26] experiments in which attempts were made to ignite loose tufts of clean and of slightly greased textile fibers in oxygen and in oxygen-enriched air by means of sparks whose energies and voltages were representative of those that might be expected to occur in oxygen tents. Cotton, wool, nylon, rayon, and cellulose acetate were tested. "The frequency of ignition obtained in all tests was about one ignition in 400 sparks."

[This study shows that the possibility of ignition of a diver's clothing by static sparks cannot be ruled out, even though the ignition probability is not high. Further work [34] on this subject is to be done at the Bureau of Mines.]

A general discussion of the static spark problem has been published by Anderson [1]. Following is a quotation from this article: "Only the surfaces of a film or other object need be rendered conductive for total bleed-off of a static charge to be made possible by grounding. This accounts for the widely held misconception that moist air is a good conductor. Actually, air is a superb insulator, and its almost infinitesimal conductivity is in reality somewhat decreased by the presence of moist vapor [52]. The apparent antistatic effects of moist air are due to the formation of an adsorbed, microscopic film of moisture on the surface of a solid insulating material in such a moist atmosphere."

[The DuPont Company has suggested [5] that to control static on a cloth, 4% "Ethoquad C-12" be applied in the final rinse water after each laundering.]

L. Contamination Problems

Outgassing of small quantities of potentially toxic materials is a much greater problem in space vehicles, where there are extreme weight limitations, than in chambers on earth, where it is easier to discard contaminated gases. Nevertheless, the possibilities of outgassing from materials in hyperbaric chambers should not be overlooked.

Some of the problems have been discussed by Mader and Mills [39], and these authors also carried out experimental work.

The apparatus used to derive the outgassing properties of materials consisted of 72-liter Pyrex flasks used as reaction chambers. Each flask was covered with a tight-fitting stainless-steel lid and was equipped with several inlet tubes which were either connected to air purification systems or gas handling systems. The tubes were capped with serological stoppers for injection or withdrawal of samples from the flasks. Test materials of known weight and surface area were then suspended from the center of each flask. Since test runs at ambient temperatures involved waiting periods in the order of 30 days and longer, an accelerated procedure was adopted. All outgassing tests were conducted at a temperature of 120°F for a period of 24 hours. Materials to be tested were introduced into 72-liter flasks and irradiated by four mercury-vapor lamps.

Pressure within the flasks was adjusted to 0.5 atm. composed of 50% oxygen and 50% nitrogen. After a curing time of one day, gas samples were withdrawn from the flask for gas chromatographic and infrared analysis. Three flame ionization gas chromatographs with dual columns and dual detector systems were calibrated with approximately 150 compounds expected to be either outgassed into the reaction chamber or to be present in space cabins. Identification of individual peaks was based on elution ratios, using three different substrates at two column temperatures. In some instances, large-volume samples were withdrawn from the reaction flasks and condensed at liquid nitrogen temperature. They were used for infrared confirmation of existing peaks or to determine compounds undetectable by gas chromatography.

Before establishing 120°F as the test temperature, a comparative analysis was made of the effects of three different temperatures on quantities and types of outgassing compounds. The temperatures selected were: 80°F, 120°F, and 200°F. Gas chromatographic as well as infrared analyses of the evolved products indicated that the increase in temperature from 80°F to 120°F affected only the quantity

of the released compounds. The types of the outgassed species remained essentially the same, although on close inspection certain differences in detail were noticeable.

[Detailed results were not reported in the article. Some general conclusions:]

A water-based methacrylate paint was found to release the smallest amounts of outgassing products, while the other two paints tested--epoxy paint and polyvinyl acetate--released large amounts of entrapped solvents which increased in concentration to toxic levels.

A number of outgassing tests with glass wool-asbestos ribbons used as insulators inside space cabins, showed the release of large amounts of organic compounds, although the material had been flash-fired by the manufacturer at 700°F.

It is dangerous to use chlorinated hydrocarbons, even trichloroethylene, for the final cleaning.

[In connection with this subject, see also the next part (M) of this report, in which there is some discussion of toxic products that might be evolved as a result of the heating of treated textiles.]

M. Flame-Retardant Treatment Methods for Fabrics

Coleman [16] found a boric acid - borax treatment to be effective for cotton, but the flame-retardant chemicals were washed out during laundering and were destructive of the fabrics.

Some phosphorus-containing chemicals are used for temporary treatment, i.e., the chemicals wash out during laundering. However, the most interesting treatments are those which result in cloth from which the flame-retardant chemicals are not leached out to an important extent during washing. Apparently the original work on these was done at the Southern Regional Research Laboratory (at New Orleans) of the U.S. Department of Agriculture. This laboratory developed the use of tetrakis hydroxymethyl (phosphonium chloride), THPC [47]; of tris (1-aziridinyl) phosphine oxide, APO; and of the two in combination [23]. The THPC treatment was then further developed by Hooker Chemical Corporation (this work led to the "Roxel" line) and by Proban, Ltd., in England [46]. The APO treatment was further developed by the Dow Chemical Company [37]. THPC has the chemical formula $(HOCH_2)_4PCl$, and APO is $(CH_2CH_2N)_3PO$. With regard to THPC, the Hooker Company supplied us with the following, which originated from Proban, Ltd. [46].

"When a piece of Proban-treated fabric is exposed to the action of a flame, there is charring and decomposition with evolution of very acrid fume, just as when the same fabric untreated is pyrolyzed

in too little air for complete combustion. There is only a very slight loss of phosphorus in the fume evolved from the Proban-treated fabric. Nevertheless the fume from, for example, test strips of cloth to which a flame test is being applied, is thoroughly unpleasant, and good ventilation should be provided - preferably by use of a laboratory fume cupboard."

With regard to possible toxic effects of these fumes, experiments were conducted by Proban, Ltd., "with the assistance of a competent medical authority. Test animals (rats) were exposed to the fume produced by destructive distillation of Proban-treated cloth. Even when the exposure was so severe that the rats appeared unconscious they rapidly recovered, on removal from the chamber, from the acute effects. It was concluded that charring the Proban treated cloth did not produce any substance of toxicity exceeding that of the products generated by charring untreated cotton.

A study of the toxic products evolved during the heating of THPC-treated cloth was made at the Southern Regional Research Laboratory [53]. A sample of cotton cloth was treated in the usual way and then charred. Upon charring, the fabric retained 95.6% of its phosphorus content. Of the volatile material, only a small proportion was the toxic compound phosphine; it was estimated that the evolved PH_3 constituted 0.0019% of the weight of the treated fabric. Most of the volatile material "should consist of phosphoric acid, phosphine oxides," and related compounds.

The APO treatment developed by Dow has been described by LeBlanc [37]. This treatment involves the use of thiourea in addition to APO. Although APO is a toxic compound, the toxic aziridinyl rings are destroyed during the pyrolysis which occurs on curing of the flame-retardant cloth; this leaves the phosphorus in a physiologically inert condition.

Drake [23] has described the combined THPC-APO treatment developed at the Southern Regional Laboratory. The following is from this article:

"Cotton fabrics treated with APO-THPC have features which make them far superior to any previously known flame-retardant treated cotton fabrics. APO-THPC-treated fabrics are durable to repeated laundering and dry cleaning; are glow resistant as well as flame resistant; when exposed to flames or intense heat [they] form tough, pliable, and protective chars; are inert physiologically to persons handling or exposed to the fabrics; are only slightly heavier than untreated fabrics; and are susceptible to further wet and dry finishing treatments. In addition, the treated fabrics exhibit little or no adverse change in hand, texture, and appearance, and are shrink-, rot-, and mildew-resistant. The treatment reduces strength only slightly. Finished fabrics have 'easy care' properties in that they are wrinkle-resistant and dry rapidly."

"Applications of APO-THPC flame retardant finishes are being made by numerous textile finishing mills, but for the most part are [used] for relatively small yardages to produce fabrics, both cotton and cotton-synthetic blends, for military research studies, and for customer-acceptance studies."

"APO-THPC treated bed sheets have gone through 100 institutional launderings and still passed the Standard Vertical Flame Test. To the best of our knowledge, fabric adequately processed with the APO-THPC flame retardant will pass any of the known standard flame tests."

N. Standard Test Methods for Flame Resistance

All standard test methods that have come to our attention are for air at atmospheric pressure. From the point of view of our current study, therefore, these methods are not very helpful. Nevertheless, they are reviewed here because they are often referred to in the literature. It is handy to have such a review in a single place.

For details, see original specifications. The following partial descriptions give only some of the principal points.

1. American Society for Testing and Materials (ASTM)

ASTM: D 626 - 55 T "Fire-Retardant Properties of Treated Textile Fabrics."

Specimen size: 2 x 12-1/2 inches.

Procedure: Adjust the Bunsen or Tirrill burner so that it has a luminous flame 1-1/2 in. above the top of the burner. Suspend the sample vertically 3/4 in. above the top of the burner. Apply the flame for 12 sec. and then withdraw it. Record the time during which the flaming continues. To determine Length of Char, remove the specimen from the clamp and insert hooks in the specimen, one on each side of the charred area, 1/4 in. from the adjacent outside edge and 1/4 in. from the lower end of the specimen. Holes may be punched in the cloth for the hooks with an office paper punch. Attach a "tearing weight" to one hook, the weight, inclusive of the hook, being equal to approximately 10 per cent of that required to tear the unburned cloth. Apply the weight to the specimen gently without impact by raising the other hook. The length of char shall be the distance from the end of the specimen which was exposed to the flame, to the end of the tear made lengthwise of the specimen through the center of the charred area. (See AATCC 34-1966 for a helpful picture that shows part of the technique for determining the char length.)

To pass the test, flaming after withdrawal shall not exceed 2 sec., the average length of char shall not exceed 3-1/2 inches, and the maximum length of char for any one specimen shall not exceed 4-1/2 inches.

ASTM: D 1230 - 61 "Flammability of Clothing Textiles."

Specimen size: 2 x 6 inches.

Procedure: Specimens cut from the textile are prepared by brushing if they have a raised fiber surface, by dry cleaning and laundering if they have a flame-retarding finish, and by drying. The dried specimen is held in special apparatus at an angle of 45°, a standarized flame is applied to the surface near the lower end for 1 sec., and the time required for the flame to proceed up the fabric a distance of 5 in. is recorded. Ignition or fusing of the base (i.e., the main part) of fabrics having a raised fiber surface, is noted.

Three classes of flammability are described in detail. Class 1, normal flammability: (a) Textiles that do not have a raised fiber surface but have a time of flame spread in the test of 3-1/2 sec. or more. Textiles having a raised fiber surface that have a time of flame spread in the test of more than 7 sec. or that burn with a surface flash (time of flame spread less than 7 sec.), provided the intensity of the flame is insufficient to ignite or fuse the base fabric. (b) and (c) refer to more rapid burning.

ASTM: D 1692 - 59 T: "Flammability of Plastic Foams and Sheeting."

Specimen size: 2 x 6 inches (5 x 15 cm).

Procedure: Each specimen is marked across its width by two lines (gage marks) 1 and 5 in. from one end of the specimen. The specimen is then laid horizontally on a 1/4 inch mesh metal cloth, which supports the sample. The specimen is ignited at one end by a blue flame from a burner with a wing top. The support cloth is 1/2 in. above the top of the wing top. The visible portion of the blue flame should be 1-1/2 in. high. At the end of 1 min., or when the flame front reaches the first gage mark, remove the burner.

If no evidence of ignition, the specimen is nonburning by this test.

If the specimen burns, measure the burn rate between the two gage marks (4 in. apart) with a stop watch. If the flame goes

out before reaching the second gage mark, the specimen is self-extinguishing by this test.

2. National Fire Protection Association (NFPA)

NFPA 701: "Flameproofed Textiles." The "small-scale" test is similar to ASTM D 626 - 55 T (above) [23]. We have not yet seen the original method.

NFPA 702 - 1962: "Flammability of Wearing Apparel".

Specimen size: 2 x 6 inches.

Procedure: Samples are tested at an angle of 45° in a draft-proof chamber 14-1/2 in. wide x 8-1/2 in. deep and 14 in. high. The sample is ignited at the lower end by a butane gas jet 5/8 inch long. The time of flame spread of the textile is measured.

In a variation of this test for non-textiles, specimens 2 x 12 in. are supported in a vertical position, and the bottom edge exposed for 10 sec. to a luminous Bunsen burner flame approximately 1/2 in. in diameter and 1-1/2 inches long.

3. Underwriters' Laboratories (UL)

UL 214: "Flame Tests of Flame-Resistant Fabrics."

Two tests are described, the small scale and the large scale. A fabric must pass both in order to be UL approved.

Small-scale specimens: 2-3/4 x 10 inches.

Small-scale procedure: Specimens are clamped along the long edges and suspended vertically. A sample is ignited by a Bunsen flame at the lower end; the flame is withdrawn after 12 sec. The length of char is determined as in ASTM D 626 - 55 T; the UL instructions give a table of "tearing weights", which vary with the weight of the cloth.

Large-scale specimens: (A) 5 x 84 inches (or not less than 30 inches, or the full width of the goods). (B) Specimens 25 inches wide and 30 to 84 inches long, folded four times in the direction of length.

Large-scale procedure: Specimens are suspended vertically. They are lightly restrained laterally with clamps and guide wires attached to the outer edges. Specimens are ignited at the bottom with a Bunsen flame, and the flame is to be withdrawn after two minutes. The folded specimens are suspended vertically with the folds half an inch apart and the edges of the folds facing the observer.

UL give detailed instructions for judging whether the fabric

passed the test. Among these is: in either the small or the large-scale tests, the fabric shall not continue to flame more than 2 seconds after withdrawal of the flame.

4. American Association of Textile Chemists and Colorists (AATCC)

AATCC 34 - 1966: "Fire Resistance of Textile Fabrics".

Specimen size: 2-3/4 x 10 inches.

Procedure: A specimen is suspended in the vertical position and ignited at the bottom with a gas flame, which is withdrawn after 12 sec. Time of flaming and glowing after withdrawal of the flame are measured with a stop watch, and the length of char is measured in the usual way. The instructions for measuring length of char are made clearer by a picture.

5. U.S. Government, Federal Specifications

All of the following are part of Federal Specification CCC - T - 191b, May 15, 1951, or of amendments thereto.

Method 5900: "Flame Resistance of Cloth; Horizontal".

Specimen size: 7 x 10 inches.

Procedure: Specimen is held horizontally and heated with a flame produced by burning 0.3 ml of absolute alcohol. The charred area of the specimen is measured.

Method 5902: "Flame Resistance of Cloth; Vertical".

Specimen: 2-3/4 x 12 inches.

Procedure: The specimen is held vertically by the edges and ignited at the bottom with the flame of a burner. The burner is withdrawn after 12 seconds. The flaming time, glow time, and char length (see AATCC 34 - 1966) are recorded.

Note: This method was slightly modified in 5903 - T (January 15, 1959). T stands for tentative. 5903 - T is part of Amendment 4, Part 4, issued January 15, 1959.

Method 5904: "Flame Resistance of Cloth; Vertical, Field."

This is a field test, and can be made on a piece of cloth of any size (at least six inches long) which has an edge that can be placed in a horizontal position for testing. An area 2 inches

wide and 5 inches deep is cut from the center of one end of each of two metal plates. The plates are then clamped over the fabric, one plate on each side. A candle is used as the ignition source. The candle flame is placed under the lower end of the sample, and withdrawn after 12 seconds.

The flaming time shall be the time the material continues to flame after removal of the candle flame from the specimen. Char length shall be the distance from the edge of the specimen to the end of a tear through the charred area, made by hand with enough force to tear through the charred or scorched portion but not of sufficient force to break undamaged yarns.

Method 5906: "Burning Rate of Cloth; Horizontal".

Specimen size: 4-1/2 x 12-1/2 inches.

Procedure: The specimen is clamped along each long edge and ignited at one end with a flame from a Terrill or Bunsen burner. The burning rate is measured with a timer between 2 heat-resistant marking wires 10 inches apart.

Method 5908: "Burning Rate of Cloth; 45° Angle".

Specimen size: 2 x 6 inches.

Procedure: There is an automatic timing mechanism. When actuated, a gas jet is automatically applied near the bottom of the specimen. When the fabric flame reaches a cotton thread, The thread is burned through. This releases a weight which stops the timing of the burn rate.

Method 5910: "Burning Rate of Cloth; 30° Angle".

Specimen size: 1 x 6 inches.

Procedure: The specimen, held between two metal grill-like frames, is ignited by holding a match to the lower end for 5 sec. The burning rate is measured with a stop watch or other timing device.

Foreign standard methods have not been summarized above. Wraight and Thomas [59] mention some British methods. They measured rates of flame spread up fabrics both vertically and at an angle of 45° and found that there was a simple linear relationship between the results obtained by the two methods. Thus, if either method is less convenient than the other, the results that

would be obtained by it could be calculated from the results at the other angle. [Our experience at Tonawanda, however, indicates that experimental results with samples in the vertical position are less reproducible than if the tests are carried out at a 45° angle.]

P. Hydrogen-Oxygen Mixtures

As part of the work under this contract during the coming year, it is proposed to study the fire hazards in mixtures of hydrogen and oxygen.

[A very interesting article [62] was published in 1945 by Zetterström in Swedish. We obtained a translation through the courtesy of Peter Edel.] Zetterström discusses various possible diluents for oxygen to be used in deep diving. In 1909, Schrötter proposed replacing nitrogen with hydrogen or methane. In 1920, the use of helium was proposed and became common, at least for American divers, because helium was not too costly in the U.S. Use of methane is ruled out because it is strongly narcotic (too soluble in body tissues). Therefore helium, neon, and hydrogen are the only low-molecular-weight gases that can be considered as substitutes for nitrogen. [Hydrogen has the great advantage over helium for deep diving of being less dense, and therefore easier to breathe, than helium.] The resistance to breathing is proportional to the square root of the density.

In September, 1943, Zetterström proposed the use of hydrogen for diving to the Swedish Admiralty. The system hydrogen-nitrogen-oxygen forms a non-explosive mixture as long as the oxygen content is 4% or less. Such a mixture can be compressed and heated without risk. [No source for this information is given in the article.]

In experiments begun in 1943, Dr. Yngve Zetterman showed that hydrogen at various partial pressures was not toxic to cats and other animals.

Hydrogen distorts the human voice [in a manner similar to that of helium. Also like helium,] hydrogen has the disadvantage that its great thermal conductivity makes a diver feel cold unless the diving suit is heated.

Zetterström himself successfully used a hydrogen mixture for breathing during a dive at 110 meters (361 feet) on December 14, 1944. He found the resistance to breathing to be small at this depth, and he found that there appeared to be no poisoning effect.

In 1940, British professor J.B.S. Haldane conducted an experiment in which the subject first breathed air at a pressure

of 10 atm, and was then switched over to a hydrogen breathing mixture. It was found that the narcotic effect of the nitrogen disappeared rapidly.

[If Zetterström's safety limit of 4% O_2 is correct, safe change-over during diving can be carried out by substituting a mixture of 96% H_2 + 4% O_2, carried on shipboard, for a mixture of He + N_2 + O_2 containing 4% or less oxygen. The reverse change can similarly be made while the diver is ascending. Thus the oxygen concentration would never exceed 4% during diving operations. The mixture of 96% H_2 and 4% oxygen could be made on land with the cylinders located in back of a safety barrier during filling; this mixture, once produced, would be permanently safe and could be stored under pressure and transported on shipboard until needed.]

Bjurstedt and Severin [6] published a paper on the use of hydrogen for deep sea diving.

"The risk of explosion in the handling of hydrogen-oxygen mixtures seems to have discouraged the testing of this gas mixture for deep-diving purposes. This risk, can, however, be avoided if, as already pointed out by Case and Haldane [10], the oxygen percentage is kept at 4 or below."

Hydrogen seems to be as chemically inert in the body after inhalation as the noble gases.

pp. 113-114. Decompression when the diver has been breathing hydrogen-containing mixtures is discussed in the article.

p. 114. From the results of decompression experiments on rats and cats in a small decompression chamber and from the various factors which could be assumed to be involved in the uptake and elimination of gaseous hydrogen by the body, a computation of decompression tables and curves for divers was made by Professor Zotterman. He included depths of 70, 90, 100, 110, 140, and 160 meters.

p. 115. During his last diving experiment, Zetterström was accidentally killed, as mentioned in a preceding article. However, he safely reached a depth of 525 feet and reported that no sign of narcotic effect was noticed, and that the inhalational resistance was no greater than with ordinary air at 130 feet. No ill effects from the hydrogen were reported.

According to Coward and Jones of the U.S. Bureau of Mines [20], there is a great variation in measurements of the limits of flammability in hydrogen-oxygen mixtures, depending upon the experimental conditions.

p. 19. The worst condition tried was upward propagation in a closed tube 2 inches in diameter at 1 atm. pressure; here the limit was 4.2% oxygen. For downward propagation, limiting oxygen concentrations as high as 8% have been measured. [The figure of 4.2% is the safest, and is very close to the value of 4% mentioned by Zetterström, who apparently made no measurements of his own on the flammability limits.]

We have found only one report on the effect of pressure on this flammability limit. Strauss and co-workers [54] measured the flammability limits at two pressures; they found them to be 7.47% O_2 at 1 atm. and 4.26% O_2 at 15 atm. abs. [Since no measurements were made at other pressures, there is no indication of the shape of the pressure-vs.-% O_2 curve.] [We plan to carry out some experiments on this subject during the second year of our Navy contract. Since an oxygen concentration of less than 2% would probably be sufficient for breathing at depths of 600 feet or more, the probability is that hydrogen could be used quite safely.]

The Bureau of Mines Laboratory in Pittsburgh [33] has informed us that they have no information on the upper flammability limit for H_2 - O_2 mixtures at pressures above 1 atm. However, they kindly sent us suggestions for experimental methods for studying the situation.

Q. Books

The two books on the subject of combustion which we have found most helpful are by Roth [48] and by Williams [58]. For a general background, we have also found Lewis and Von Elbe [38] useful.

R. Methods of Measuring Burn Rates

Some of the methods used by others to measure burn rates of fabrics (or of thin sheets of materials other than fabrics) are given below. All of these differ from the method used by us.

1. Visual observation and timing with a stop watch or other timer. The time may end either when the flame reaches a predetermined marker on a strip of sample, or when the sample has been completely consumed.

2. Calculation of the rate from moving picture photography [30].

3. In the case of spontaneously incompletely burned samples, weighing of the sample at the beginning and at the end of burning,

coupled with timing. A variation is to drop the burning sample into water after a given time interval, and then to dry and weigh what is left unburned [22].

4. Automatic timing from the start until a cotton thread, located in a desired position, burns through.

5. Suspension of the specimen from the arm of a torsion balance. The flame speed is calculated from a photographic trace of the loss of weight with time [36].

6. Attaching fuse wires to the sample strip at known intervals. The fuse wires are connected to a timer.

V. APPARATUS AND TECHNIQUE

A few preliminary burning tests were made in the open air of the room and some in a 4-inch diameter pressure vessel, but most of the tests were carried out in a 6-inch diameter stainless steel vessel.

A. The Four-Inch Diameter Pressure Vessel

The 4-inch diameter vessel had an internal effective length of 20.5 inches. The vessel and auxiliary equipment are sketched in Fig. 2. Fig. 3 is a photograph of the vessel in the vertical position, with flanges in place; this photograph also shows some of the auxiliary apparatus, including the Heise absolute pressure gage. Fig. 4 is a photograph of the open top of the vessel and of the upper flange hanging from a cable well above the vessel. Suspended from the flange, and ready for insertion into the vessel, are the sample holder with a paper strip mounted on pins, and the electrical and thermocouple connections. (The sample holder shown in Fig. 4 has two rows of pins. This system was abandoned in favor of just one row of pins. Samples are easier to mount on, and yet are held securely by, the pins in a single row.)

The heavy upper flange was held by a cable which passed over two overhead pulleys and thence down to a counterweight.

The four-inch vessel consisted of a 4-inch I.D. stainless steel pipe, 16 inches long, welded on both ends to 600-psi carbon-steel flanges suitable for temperatures up to 1440°F. The pressure vessel was cleaned to meet Union Carbide-Linde safety standards for oxygen service, and hydrostatically tested to 1000 psi. The left-hand flange in Fig. 2 had an O-ring groove for use with a Viton O-ring. Fitted through the left-hand blank

flange were two Conax glands; through one of these passed the thermocouple wires, and through the other the wires to supply electrical power for heating the platinum-wire igniter. The right-hand flange had a 500-psi safety-release valve.

Soft-soldered to the inside of the left-hand blank flange was the rod of the sample holder, which is shown in detail in Fig. 5. The sample was mounted on a series of pins. Progress of the combustion was sensed by three platinum platinum-rhodium thermocouples wired in series. The output of the thermocouples was recorded on the strip chart of a variable-zero, variable-span Brown Electronik potentiometer-type recorder, partially shown in Fig. 3. The pen could travel full scale in 2 seconds, and the chart speed was 24 inches per minute. Pressure was read on a 1000-psia, calibrated Heise gage.

The procedure used in experiments conducted in the four-inch vessel was (except for the necessity of unbolting the top flange for every run) essentially the same as the one employed for the six-inch vessel (see below).

B. The Six-Inch Diameter Pressure Vessel and Auxiliary Equipment

1. Description of Vessel and Sample Holder

This vessel (Figs. 6-13) represents a great improvement over the 4-inch diameter vessel used in the early exploratory work carried out at Tonawanda. The new vessel is 6 inches in I.D. The main body of the vessel is a piece of six-inch-pipe-size Type 304 stainless steel pipe 20 inches long. The head and bottom closures are made of Type 304 stainless steel. The head closure is of a special type that locks with the rotation of one-eighth of a turn and seals on a Viton O ring. The rotation is accomplished by hand and does not require the use of tools. Thus a new sample may be inserted easily and quickly. In the old vessel, eight nuts (Fig. 4) had to be removed from the bolts holding the head closure each time a new sample was to be inserted.

The new vessel is equipped with a two-inch-diameter laminated-glass window designed for a working pressure of 600 psi (about 1350 fsw). The window housing, made of carbon steel, can be seen in the photographs (Fig. 6 and 7) towards the bottom of the vessel. The vessel is equipped with a 700-psi bursting disc, mounted on the side of the vessel opposite to that on which the window is located. The bursting disc assembly is visible in Fig. 7.

With the bursting disc assembly closed off, but with the window in place, the vessel was hydrostatically tested at 1000 psig. The safe working pressure is therefore at least 600 psi.

In Fig. 6, the closure is seen lying on the bench in front of the vessel. Extending from the closure is a 1/4-inch diameter rod on which are mounted the sample holder, the wires which bring electrical power to the igniter, and the thermocouple wires. The thermocouple wires and the wires which bring electrical power to the igniter are led into the vessel through Conax pressure fittings in the head closure.

The sample, usually in the form of a strip either 6 or 12 mm wide and about 160 mm long, is mounted on a single row of brass pins half an inch apart, sketched in Figure 14. Combustion rates are measured between thermocouple junctions mounted on the same brass support as the one which holds the pins. The newer sample holder shown in Figure 14 is similar to the old one (Fig. 5). In the new one, a Chromel-A resistance wire igniter was substituted for the platinum wire igniter, and three 28 ga. Chromel-Alumel thermocouples wired in parallel were used instead of the three platinum platinum-rhodium ones wired in series, used on the original sample holder for the four-inch vessel.

The Chromel wire igniter was so designed that it tightly held one end of the sample during ignition.

For runs in the vertical position, it was found that the burn rates could be better measured with only two thermocouples instead of with the three shown in Fig. 14. With three thermocouples, the peaks on the chart were too close together, or too indefinite.

The combustion chamber can be used at any angle from horizontal (0°) to vertical (90°). When the chamber is mounted at an angle greater than 0°, the igniter is at the lower end of the sample, so that the flame will burn upwards. The igniter is heated by a measured quantity of electricity.

In Fig. 6 the vessel is shown at an angle of 45°. The projection near the bottom is the housing for the high-pressure window. Lying on the bench is the vessel closure, to which is attached the sample holder. The holder is mounted on a rod centered inside the vessel when in place. The white tape which holds some of the wires on the rod between the sample holder and the closure is "Scotch" Brand Electrical Tape No. 27, glass cloth thermosetting. The coating on this cloth was combustible, and when it burned, the remaining glass cloth was not strong enough to hold together. The tape was therefore replaced by a piece of copper wire, which proved to be satisfactory.

Insertion of a sample is portrayed in Fig. 7.

2. Auxiliary Equipment

Three strip chart recorders were used to measure and record the data. (1) One of these, an Esterline Angus "Graphic Ammeter", was used to measure the igniter current and the length

of time the current was on. (2) The second showed the temperature of the igniter; a blip in the pen line on the chart indicated the instant at which the power was turned on. About a quarter of a second after the blip occurred, there was a drastic change in the slope of the line; this change of slope showed that the igniter was becoming hot. A second, less drastic, change of slope indicated the time and the temperature at which ignition of the sample occurred. (3) The third recorder showed the response of the thermocouples to the heat of the flame as the latter passed upward along the sample strip.

Some of the auxiliary equipment for the combustion chamber is shown in Fig. 15, along with a small sketch of the 6-inch vessel. For some runs (explained later), the water bubbler is replaced by a vessel of water which can conveniently be heated.

3. Ignition of the Sample

The standard tests for flame resistance at one atm. abs. pressure involve the use of gas flames for ignition. However, use of burners presents considerable experimental difficulties at pressures greater than atmospheric. Moreover, a hot wire is sometimes more effective than a flame. This is probably because the wire can be heated to a higher temperature than the flame of a match or cigarette lighter. For example, we were unable to ignite a sample of Nomex cloth with a flame in air, but this fabric could be ignited in contact with the hot wire (Table 15). However, in one case the reverse was true. Samples of Wondershield-plain mattress ticking could not be ignited, even in 100% oxygen at 1 atm. pressure, with the Chromel igniter. It was necessary to stick a piece of cellulose adhesive tape to the bottom of the sample and to ignite the tape with the hot wire in order to set afire the very thin coating on the Wondershield.

Another possible ignition source is a spark, but use of a hot wire is more convenient, and has the further advantage that the ignition source stays in continuous contact with the sample while ignition is being attempted.

The approximate ignition temperature was measured, in many cases, by means of a chromel-alumel thermocouple welded to the igniter wire. The part of the igniter wire that was not near the thermocouple junction was undoubtedly hotter than the measured temperature because some heat was conducted away by the thermocouple lead wires, but the results gave good relative values for the temperature required to ignite the samples.

Experience showed that the burning of many samples caused deterioration of the thermocouple junction on the igniter, which in turn caused the igniter to burn out. After the first runs,

therefore, a thermocouple was not welded to the igniter unless it was necessary to measure the ignition temperature. This increased the life of the igniter and made it much less costly to install new igniters.

4. Preparation of the Gas Mixtures

Twenty-six cylinders of gases were used during the work. One of the gases was standard U.S.P. oxygen, which contains about 99.6% oxygen and 0.4% argon. The other 25 were oxygen-containing mixtures, prepared well ahead of time in regular steel "K"-size pressure cylinders, given time to mix well, and then analyzed by gas chromatography. The percent of oxygen was verified with an Orsat gas analyzer by absorption of oxygen in alkaline pyrogallol.

5. The Procedure in Brief

To make a test, the sample and sample holder are sealed inside the pressure vessel. The latter is evacuated. From then on, the procedure varies according to whether the final test is to be made at a pressure below, at, or greater than one atmosphere. In the latter two cases, the gas to be tested is saturated with water vapor by slowly admitting it through a water bubbler at room temperature until atmospheric pressure is reached; when this happens, gas starts to bubble out through a mercury bubbler. The pressure in the vessel is read on the Heise gage. To attain higher pressures, the water saturator and the mercury bubbler are bypassed (Fig. 15). Electrical power is turned on until ignition takes place and the power is then switched off. The length of time the power is on is recorded automatically. The other necessary information is automatically recorded as explained above.

For runs to be made at pressures below one atm. abs., a mercury manometer is used instead of the Heise gage, since the gage cannot be read with sufficient accuracy at low pressures. First water vapor (from outgassed hot water) is admitted to the evacuated vessel until the pressure is about equal to the vapor pressure of water at room temperature. After that, dry gas is admitted until the desired pressure is reached.

Some runs are made without any addition of water vapor. When that is the case, it will be indicated in the text or table by use of the term "dry gas".

From the recorded data, the following can be determined:

Power supplied to igniter.

Length of time elapsed before ignition takes place.

Approximate temperature of the igniter, and thus the approximate ignition temperature of the sample.

Rate of combustion of the sample.

6. Details of the Procedure When the Pressure is to be Atmospheric or Greater

(1) The sample strip is installed on the sample holder. One end of the strip is inserted into the heater grid in such a manner that successive loops of the grid are on alternate sides of the strip to afford maximum contact. The strip is then pulled taut and fixed on the support pins in a position horizontal to the base of the sample holder.

(2) The sample holder with sample attached is inserted into the pressure vessel. The latter is sealed by rotating the head one-eighth of a turn.

(3) The vessel is evacuated until the minimum pressure readily attainable by the mechanical pump (about 28.5 inches of mercury on a vacuum gauge) is attained. The Heise pressure gauge is then adjusted to 0 psia.

(4a) With Valve A (Fig. 15) closed and Valves B and C open, the desired gas mixtrue is slowly passed through a water bubbler and into the evacuated vessel until atmospheric pressure is attained. Valves B and C are then closed, Valve A is opened, and dry gas is admitted until the desired pressure is reached. If the gas mixture thus admitted is not the same one used in the previous run, Steps 3 and 4 are repeated to flush out the gas in the lines and the small quantity of residual gas left in the pressure vessel after evacuation.

(4b, alternate to 4a). When no moisture is to be added, the dry gas is added through Valve A. This is the case whenever the most drastic conditions are to be tried, as for a sample of material to be tested for non-flammability, or in determining the region of non-combustion.

(5) Sometimes there is at this time a two-minute waiting period for the sample material to come to more complete equilibrium with the moisture content of the gas. For a discussion of the two-minute wait, see Section VI, "Preliminary Experiments."

(6) The graphic ammeter, the igniter temperature recorder, the burn rate recorder, and the switch for power to the igniter are all turned on.

(7a) When the operator is sure that ignition of the sample has occurred, he turns off the power switch (current to the igniter), the ammeter, and the ignition temperature recorder. The surest way to determine whether or not a sample has burst into flame, is by observation through the window. In the case of filter paper or other materials that ignite readily, the power

switch is usually turned off when there is an increase in the slope of the pen line on the chart of the igniter temperature recorder. If an igniter without a thermocouple is used, the moment of ignition is determined either visually or by the response of the burn rate recorder.

(7b; alternate to 7a) If the sample does not ignite, or if smoldering is observed through the window, the power to the igniter is left on for a sufficient length of time for the igniter to reach maximum temperature and to be in contact with the sample long enough to make sure whether or not the sample will burn with a flame.

(8) The burn rate recorder is turned off after the sample has stopped burning.

(9) The pressure in the vessel is reduced to atmospheric by opening of the vent valve.

(10) The head closure is rotated 1/8 of a turn and removed in order that the operator may observe any residue remaining on the pins of the sample holder.

(11) The points of interest on the three strip charts are labeled. The necessary calculations are made and all results are entered in the notebook.

7. Details of the Procedure When the Pressure is to be Less than One Atmosphere Absolute

Same as under Part 6. above, except item (4), which becomes:

(4a) Water vapor from hot, degassed water is admitted until the pressure, read on a mercury manometer, is approximately that of the vapor pressure of water at room temperature. Valves B and C (Fig. 15) are then closed, and the gas is admitted through Valve A until the desired pressure is attained. Pressures below atmospheric are read on a mercury manometer (either the open-end or the closed-end type) because the Heise gage is not sufficiently accurate in this pressure range.

VI. PRELIMINARY EXPERIMENTS

A. Choice of Standard Material

Most of the combustion experiments were made with samples of paper because it burns readily, and therefore represents one

of the fire hazards in a diving chamber. Several different kinds and sizes of paper were tried. A standard type of filter paper was finally selected because it burns fairly steadily and it is readily available in laboratories throughout the world. The size of the sample was standarized at 6 mm wide by 155 mm long.

As our standard filter paper, we selected Whatman No. 1, made in England by W. and R. Balston, Ltd. The label on one package stated that the average ash per 18.5 cm circle = 0.0014 gram.

B. Exploratory Tests

The earliest work was carried out either in the open room or in the four-inch diameter vessel described in Section V above. In the 4-inch vessel it was found that: (1) filter paper strips burned slightly slower in a water-saturated gas mixture than in the same mixture but without added water vapor, (2) the rate of combustion was much greater when the filter paper strips were held in the vertical position than when they were horizontal, and (3) it was more difficult to ignite samples in a helium-rich atmosphere than when nitrogen was the diluent instead of helium, everything else being equal.

These three conclusions were confirmed by extensive later work, but a fourth apparent finding was shown to be in error. In the exploratory work, in which runs were not repeated, it appeared that there were maxima in the vertical burning rate curves under certain conditions. In particular, it appeared several times that there were maximum burn rates at a pressure of 100 fsw. Later work showed that these apparent maxima were not reproducible, and that they were fortuitous. The fact, as can be seen in Fig.16, is that in the vertical position the reproducibility is poor and that the measured burn rates are scattered over a rather large area.

C. Effect of Vessel Size

It is self-evident that if a sample were large enough to consume an appreciable proportion of the oxygen in a given vessel, the vessel size would have a great effect on the measured rate of combustion. For light-weight samples of filter paper, not enough oxygen is consumed to affect the results appreciably. In the 6-inch vessel, when an entire paper strip 6 x 155 mm in size has been burned, the average percentage of oxygen in the air at atmospheric pressure would be reduced from 20.95% only to about 20.5%. At higher pressures the change would be even less. In the 4-inch vessel used in earlier work, the average oxygen concentration would be reduced to about 20.2% by the complete combustion of the paper strip at atmospheric pressure.

Rates of combustion for a mixture of 22.5% oxygen and 77.5% nitrogen were measured in both the four-inch and the six-inch

vessels. The results were plotted in Figure 19, where the circles represent runs made in the six-inch vessel and the squares are for the four-inch vessel. It is seen that the results for the two vessels are the same, within the experimental error. Digital values read from the curve are given in the 45° column of Table 8.

With the sample holder at an angle of 45°, comparative tests were made in the open room, in the six-inch diameter vessel, and in the four-inch diameter vessel in air at atmospheric pressure. The measured average rates were 1.25, 1.21, and 1.22 cm/sec respectively. There is greater uncertainty in the open air test than in the vessels, due to drafts in the room; even a slight draft affects the rate. This would also be true in an actual diving-decompression chamber. Although the average rate was somewhat higher in the open room, the rates were all the same within the estimated uncertainty.

There is, however, another important item to be explored during the coming year. This is the effect of larger quantities of sample material. When a larger amount of flammable material burns all at once, there is mutual heating of the parts of the sample, and less opportunity for loss of radiant heat from the center of the burning zone, than for small sample strips. Combustion may be appreciably faster (providing there is enough oxygen) in a larger fire than in a small one, and some materials which are not even ignited when the sample is quite small, may burn in a larger fire.

D. Effect of Sample Angle in Air and Simulated Air

Strips of filter paper 6 mm x 155 mm were burned in a humid atmosphere in compressed air up to a pressure of 300 fsw at various angles. The results are plotted in Figure 16.

We conclude that:

(1) The burning rate is lowest when the sample is held in the horizontal position, highest in the vertical position, and intermediate in other positions.

(2) There is very little change in the burning rate in air as the pressure is increased when the sample is held horizontally (0°), but when the sample is held at a greater angle, an increase in the pressure has the effect of increasing the burning rate, at least up to a pressure of 148 psia (300 fsw) and up to an angle of 75°. The increase in rate with increase in pressure (as compared with the rate at atmospheric pressure)

is greatest at an angle of 45°. In the vertical (90°) position, the non-reproducibility is particularly bad because of the erratic contact of the flame with the unburned material above it. Thus the results are shown (in Figure 16) as an area rather than as a curve.

Similar runs were carried out in a mixture of 22.5% oxygen and 77.5% nitrogen at the same angles, except that no tests were made with the strips in the vertical position. The results are given in Table 8 and Figure 20.

E. Effect of Sample Width

The width of the strips of filter paper had to be closely controlled, because the rate of combustion along the strips was found to increase appreciably with the width. In a series of seven tests, all made at an angle of 45° with the two-minute waiting period described above, the burning rates were:

Width, mm	Burn rate, cm/sec	
	Measured	Average
6	1.72, 1.96, 1.77	1.82
8	2.36, 2.45	2.41
12	2.92, 3.29	3.11

These results indicated that a 1-mm deviation from the standard 6 mm width might produce an error as high as 0.2 cm/sec in the measured rate.

In our experiments, we controlled the width of the strips within ± 0.5 mm; the exact length did not matter, since the linear rate of combustion was measured between thermocouple junctions separated by a known distance.

Each of three strips of the filter paper (in equilibrium with the moisture in the atmosphere in the laboratory) was weighed. The weight in every case was 0.0862 ± 0.0040 gram.

F. Effect of Humidity on the Combustion of Filter Paper

Most of the experiments on the combustion of filter paper have been carried out with minimum control of humidity effects. The strips of paper are cut out of 18.5 cm diameter "circles" and stored in a closed vessel. When a strip is to be burned, it is removed from the storage vessel and mounted on the sample holder.

As described in an earlier section, when gas is admitted to the evacuated test vessel, unless for some reason the gas is to be added "dry," the gas is bubbled through water until the pressure in the vessel is one atmosphere. Any additional gas is admitted to the vessel without being bubbled through water. As soon as the desired pressure has been reached, the power to the igniter is immediately turned on and the combustion is started.

1. Experiments with very moist paper

In order to see to what extent this lack of control affected the results, the first series of tests was carried out in the open room, with filter paper treated in two different ways: (1) The strips were simply cut and handled in the open room in the usual way, with no special precautions, and stored in a closed container; these strips are called "dry" in the discussion below. (2) The strips were stored for 24 hours in a closed container in which liquid water was present to keep the atmosphere saturated with water vapor. The strips were not wet directly by the water, but they absorbed water vapor until they were limp.

The results of the combustion tests indicated that the burning rate for horizontal strips of the "dry" paper was 1.05 times as great as for the limp paper. No significant difference was observed between the ignition temperatures, 640.8 ± 22.0°F for the limp paper and 658.3 ± 14.0°F for dry paper. However, at an angle of 33° a marked difference was observed. The dry paper burned 1.2 times as fast as the limp paper. Again, there was no significant difference between the ignition temperatures, which were 678.3 ± 27.5 for the limp paper and 703.0 ± 25.9°F for the dry paper. The increase in burn rate with increasing angle was also less for the limp paper than for the dry paper, from 0.450 ± 0.070 cm/sec to 0.865 ± 0.053 cm/sec for limp paper and from 0.472 ± 0.039 cm/sec to 1.042 ± 0.084 cm/sec for dry paper at 0° and 33° angles, respectively.

2. Experiments with absorption of small quantities of water

The second series of tests was made with the purpose of seeing how much error was introduced by not giving the filter paper more time to equilibrate with the moisture in the gas mixture inside the pressure vessel. An experiment was carried out in which strips of filter paper, first dried in a desiccator over Drierite* for 16 to 24 hours,

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*A desiccant manufactured by the W. A. Hammond Drierite Company, Xenia, Ohio

were burned under identical conditions except that the time elapsed between addition of the one atmosphere of water-saturated gas and the further pressurization of the vessel was varied. The following waiting times were tried: 0, 1, 2, 4, 5 minutes and longer. The results showed that (a) a waiting time longer than 2 minutes makes very little change in the measured burning rate, and (b) the burning rate after two minutes' waiting is usually about 7% lower than for the dry paper.

3. Remarks on technique

Experiments designed to explore the effect of pressure, of angle, of gas composition, etc., differ from those described in the preceding paragraph in that we did not start with filter strips kept dry in a desiccator, but, as explained in an earlier section, with strips that were already more or less at equilibrium with the moisture content of the air in the room. In Figures 16, 17, and 21 most of the results are for experiments in which there was no waiting period; the few points labeled "humidity controlled-two-minute wait" refer to results obtained by the two-minute waiting technique described earlier. From a comparison of results obtained with and without the two-minute wait, it would appear that the waiting period is not important with respect to measuring burn rates. Apparently the filter paper, being essentially a purified form of cellulose, comes to equilibrium very rapidly with the moisture content of the test gas.

VII. THE IGNITION TEMPERATURE OF FILTER PAPER AND THE IGNITION DELAY

A. Ignition Temperature

As mentioned above, approximate temperatures were measured by means of a thermocouple welded onto the Chromel igniter wire.

Table 5 shows the measured ignition temperatures for strips of filter paper held at various angles in compressed air. When allowance is made for the uncertainty of the measurements, it is seen that the ignition temperature is about the same, for the same pressure, at all angles. In all cases, however, the ignition temperature shows a definite decrease as the pressure is increased.

Table 6 gives the measured ignition temperatures of strips of filter paper held at an angle of 45° at various pressures in a number of gas mixtures. Except for the points marked (c) and (d), it is seen that the ignition temperatures were the same, within the experimental error, when helium was

the diluent as when the diluent was nitrogen.

The result marked (c) in Table 6 is a special case. The condition of 20.3% oxygen and 79.7% helium is right on the border between combustibility and non-combustibility. In two tries out of three, it was found to be impossible, even at very high temperatures, to ignite the sample at a pressure of 1 atm. abs. In the one trial in which ignition did take place, the measured temperature was 1130°F, which is much higher than the other temperatures shown in the table.

For all cases given in Table 6 it is seen, as in Table 5, that the ignition temperature tends to decrease as the pressure increases at constant gas composition, especially during the first 600 fsw. This is probably largely due to the increased partial pressure of oxygen that accompanies the increase in total pressure. The effect is shown in Fig. 17, which shows the same data as those given for a 45° angle in Table 5.

Table 6 shows that in most cases there is a trend toward increasing ignition temperature as the oxygen percentage is decreased at constant pressure. The few exceptions are probably the result of the experimental uncertainty.

Ingition temperatures for fabrics are given in a later Section of this report.

B. Ignition Delay

Volume for volume, the thermal conductivity of helium is about six times that of nitrogen. One result of this fact is that is is more difficult to heat materials to the ignition temperature when they are in helium than when they are in nitrogen. In this respect, helium is a safer diluent than nitrogen.

Table 7 shows the length of time (in seconds) required to heat the Chromel igniter to the ignition temperature of the filter paper strips at a constant current of 5 amperes in about 20% oxygen diluted by either nitrogen or helium. The data show that in all cases it takes longer to reach the ignition temperature in the presence of helium than when nitrogen is the diluent.

VIII. AIR AND SIMULATED AIR

The effects of sample angle and an increase of pressure on the ignition temperature and on the burning rate of paper

strips in air, have been mentioned in the two preceding sections (VI and VII) of this report. In addition to the runs in compressed air, some tests were carried out in simulated air containing about 22.5% oxygen and 77.5% nitrogen.

Ignition temperatures measured for filter paper strips at an angle of 45° in the simulated air at pressures ranging from 0 to 1000 fsw are plotted in Fig. 18. It is seen that the average ignition temperature in the simulated air falls rapidly as the pressure increases. Burning rates for the same gas mixture and for the same angle are shown in Fig. 19. All experimental points are plotted on this figure to give the reader an idea of the variation in measured rates. As mentioned earlier, the results (plotted in squares) for the 4-inch diameter vessel fall within the same range as the results (in circles) obtained in the 6-inch vessel. The curve in Fig. 19 was drawn by eye to fit the points. Digital values read from the curve are given in the 45° column in Table 8. The 45° curve is given again, but without the experimental points, in Fig. 20.

Ignition temperatures (Fig. 17) and burning rates (Fig. 21) were also determined from 0 to 1000 fsw in real compressed air, but more points should be measured to delineate the shape of the curve better, especially at pressures above 300 fsw.

Some conclusions drawn from the work with air are:

1. Even at atmospheric pressure, burning rates in air can be dangerously high if flammable materials are in a vertical or near-vertical position, especially in confined spaces.

2. The temperature required to ignite paper (and presumably other flammable materials) decreases with increased air pressure. This is true even in the horizontal position.

3. Except in the horizontal and vertical positions, the burning rate of flammable materials increases as air pressure is increased. When flammables are in a vertical position, the rate of combustion is already high at atmospheric pressure and the rate does not always appear to increase with increasing pressure because of the erratic nature of vertical flame propagation.

IX. HELIUM vs. NITROGEN AS OXYGEN DILUENTS

When a diver is being decompressed after having worked under the ocean, he is in a pressure chamber filled with a mixture of oxygen and one or more diluent gases. The diluent

gases are usually nitrogen and helium. In order to find out the relative effects of these gases over a wide range of conditions, we carried out three hundred and forty-five burning rate experiments with 6 mm x 160 mm strips of filter paper held at an angle of 45° at total gas pressures ranging from 0.21 to 10.08 atm. abs. (a pressure ratio range of over 40 to 1) with 26 different, carefully analyzed gas mixtures. Five different classes of gas mixtures were used. All were saturated with water vapor: (a) pure oxygen, (b) oxygen + nitrogen, (c) oxygen + helium, (d) oxygen mixtures containing nitrogen and helium, in which the percentage of nitrogen (dry basis) was between 10.6% and 11.1% and (e) same as d, except that the percentage of helium was about equal to the percentage of nitrogen. Typical results for 7 of the 26 mixtures are given in Table 9. The composition (dry basis) of the remaining 19 mixtures is given in Table 10. Any argon present in the gas mixtures was counted as nitrogen, because the argon concentration, if any, was low.

In calculating the pressures of runs made at 1 atm. abs. or higher, the partial pressure of the water vapor was neglected. This was because the total pressure was measured with a gauge which could be read with an accuracy of only about ±1 psi.

In tabulating the runs made at pressures below 1 atm. abs., only the pressure of the dry gas was used. This could be done, because both the pressure of water vapor and the total pressure (dry gas plus water vapor) were read to about ±1 mm Hg on a mercury manometer.

The experimental results for mixtures of nitrogen and oxygen were plotted for each gas mixture. Five of the plots (Figs. 24-28) are included with this report; these plots also include the results for helium as a diluent. The best curve was drawn through the plotted points. All the best curves for the oxygen-nitrogen mixtures were then put together on a single diagram, Fig. 22. Most of the curves fell in the expected order, i.e., in order of the percent of oxygen, but in one case they crossed. The original plots were then re-examined, and it was seen that the variation in experimental rates was sufficiently great so that a valid adjustment could be made.

In Fig. 22 the short vertical lines drawn through each of the rate curves represent the pressure lines for which the partial pressure of oxygen is 0.5, 1.0, 1.5, and 2.0 atm, respectively. Ideally, the intersection of these short vertical lines with the rate curves should fall on a smooth curve. They come close to this.

The points enclosed in circles in Fig. 22 are for essentially 100% oxygen. The line labeled 21.0% oxygen

represents the results obtained with compressed air.

Figure 23 is similar to Figure 22, except that the diluent gas was helium instead of nitrogen. The experimental curves obtained for helium-oxygen mixtures (given in Figs. 24-28) all fell in their natural order as originally plotted; no adjustments were made.

From Figs. 22 and 23 it is immediately evident that the primary factors which determine the burning rate are the percent oxygen and the pressure. Stated in another way, this says that the most important single factor is the partial pressure of oxygen.

The curves shown in Figs. 24-28 were used, as mentioned above, to construct Figs. 22 and 23; they were also used to compare the burn rates when nitrogen was the diluent with the rates when helium was the diluent.

From the smoothed values of the burning rates taken from Figs. 24-28, the ratios (R_{He}/R_{N_2}) of the rates were calculated and plotted as shown in Fig. 1.

Here R_{He} = burning rate, cm/sec, when the oxygen was diluted only by helium

R_{N_2} = burning rate, cm/sec when the diluent was nitrogen

From the diagram in Fig. 1 it is seen that the relative effects of helium vs. nitrogen vary with both the percent oxygen and the total pressure. The burning rate is greatest in helium relative to nitrogen at an oxygen concentration of 30%; here the ratio R_{He}/R_{N_2} is at a maximum. As the total pressure increases, this ratio decreases. No R_{He}/R_{N_2} ratios are shown in Fig. 1 for pressures above 200 fsw, because the shape of the burning curves, Figs. 24-28, will not be known with sufficient accuracy until measurements have been made at pressures well above 300 fsw.

Computer Correlation of the Measured Rates

It was found impracticable to correlate the experimental results from so many different gas mixtures by graphical means alone. A correlation was therefore carried out by making a least-squares fit of the data to some relatively simple polynomials with the help of an IBM 360/40 computer. The simplest polynomials would be linear, and these were tried first. The calculated burning rates did approximate the measured rates fairly closely. One such equation was:

$$R = 1.11 + 11.6\ P_{O_2} - 2.81\ P_{N_2} - 2.72\ P_{He} \qquad (a)$$

where R = burning rate, cm/sec
P = partial pressure in atmospheres

This equation again shows that the most important single item in determining the burning rate is the partial pressure of the oxygen.

It is known from graphs of the type shown in Figs. 22 and 23 that the burning rates do not actually vary in a linear manner with pressure. Experimental measurements made at pressures above 300 fsw (Figs. 19, 21) confirmed the fact that the increase in burning rate as the total pressure increases, falls off at higher pressures. Therefore it was desirable to use non-linear equations for better fitting of the data. Since the most important factor that determines the burning rate is the partial pressure of oxygen, it was decided to introduce the term $P_{O_2}^2$ to give the equation a form more consistent (than that of the linear equation) with the experimental data.

Up to the present time no single empirical equation has been obtained which gives a good representation of all of the 345 experimental measurements. The best equations found so far are:

$$R = 0.994 \text{ , } 3.111\ P_{O_2} - 0.294\ P_{O_2}^2 - 0.380\ P_{N_2} - 0.417\ P_{He} \qquad (1)$$

$$R = 1.334 + 1.937\ P_{O_2} - 0.176\ P_{O_2}^2 - 0.248\ P_{N_2} - 0.210\ P_{He} \qquad (2)$$

The effect of water vapor was neglected in formulating these equations. As mentioned above, partial pressures of the gases were employed on dry basis at the lower pressure where the proportion of moisture is appreciable.

Equation 1 is applicable to mixtures containing 21% or less oxygen, and (very roughly) to pure oxygen; Equation 2 is for mixtures containing from 22% to 50% oxygen. Equations 1 and 2, although useful, are not completely satisfactory in form because (a) the calculated burning rate does not reduce to zero when the oxygen pressure is zero, and (b) the equations do not embody the type of complex variation shown in Fig. 1. (Such embodiment would rob the equations of their simplicity.)

Equations 1 and 2 together give a fairly good representation of the experimental data, as can be ssen from the statistical analysis in Table 11 and from the curves in Fig. 29, which should be compared with those in Fig. 22. A few experimental points have been plotted in Fig. 29 to indicate that the curves represent the measured rates within the experimental error.

The curve for air was omitted from Fig. 29 because it is at about 21% oxygen that the transition between Equations 1 and 2 occurs. The calculated curves for air are shown in Fig. 30, along with the experimental points.

Two points are illustrated in Figs. 31-33. (a) The experimental points are well fitted by one of the two equations,

but (b) when Equation 1 is used to calculate burn rates for 50% oxygen, the result is very poor.

The principal importance of Equations 1 and 2 is that together they successfully cover all our experimental data, even for the ternary mixtures in which both helium and nitrogen were used as oxygen diluents. Therefore one may safely conclude that no special effects occur when both helium and nitrogen are present in the same mixture. This is illustrated in Fig. 33, where the values calculated from the empirical equations are compared with the experimental results for ternary mixtures containing equal volumes of helium and nitrogen.

As seen in Fig. 34, the experimental burning rate in essentially 100% oxygen is shown rather roughly by Equation 1.

X. BURNING RATE OF FILTER PAPER IN 100% OXYGEN

Only a few tests have been made on the burning rate of filter paper in essentailly 100% oxygen. The results for an angle of 45° have been plotted (in circles) in Fig. 34, and a few of the same values were plotted in Figs. 22 and 23.

The oxygen used was Linde U.S.P. oxygen, with purity somewhere between 99.6 and 99.9%. The chief impurity in this oxygen is argon.

It is seen from Figs. 22 and 34 that the curve for burning rate increases very steeply from a pressure of 0.21 atm. abs. to a pressure of 1.0 atm. abs. This fits in well with the general conclusion reached in the preceding Section, namely that the burning rate in gas mixtures depends primarily on the partial pressure of the oxygen present.

XI. CLOTH FABRICS WHICH HAVE THE GREATEST FIRE RESISTANCE

Of the fabrics that we have tested to date, four, Beta Fiberglas, Teflon, Asbeston D67054, and Avceram CS, are outstanding in their resistance to fire. The asbeston and the Avceram are still experimental. Avceram CS, although highly fire-resistant, has apparently not yet been made into a cloth fabric for general use.

In this section, unless otherwise stated, (a) all samples were tested in the vertical position, and (b) if the gas used

was not 100% oxygen, the diluent was nitrogen.

A. Beta Fiberglas

1. Beta Fiberglas Cloth. This is a new Owens-Corning product which can be produced by either weaving or knitting. The difference between Beta Fiberglas and the types of glass fiber used to make curtains, etc., is that the Beta fibers are extremely fine; in fact, they are so fine that persons who have worn the garments, even underwear, made from the natural white cloth, are said by Owens-Corning not to have felt itching. The case is different for cloth that has been dyed, because the dye sometimes clumps the fine fibers into little bundles which are stiffer than the individual fibers and occasionally produce itching in persons with a sensitive skin.

Owens-Corning has informed us that, in making a cloth out of Beta Fibers, it is necessary to add a silicone lubricant to the extent of about 0.9% of the weight of the fibers. In the tests made by us at Tonawanda on Beta Fiberglas cloth, no evidence of the combustion of the lubricant was obtained, either in compressed air or in pure oxygen at over 2 atm pressure. Both a glowing Chromel wire and a burning piece of Scotch tape were used in trying to start combustion. Apparently the silicone is so thinly distributed on the surface of the fiber that it cannot support a flame.

A sample (4.4 oz/yd^2 Style X3810BH) of Beta fabric was supplied by Mr. J. J. Dillon of Owens-Corning's Product Development Laboratory. When a match flame was held to the bottom of a vertical strip of this sample in the air of the room, there was no burning or charring, and the main body of the fabric did not melt. However, some of the fine fibers that protruded from the cloth melted.

At the time of the writing of this report, untreated Beta cloth suitable for making clothing is not yet sold on the open market, but can be obtained in experimental quantities by arrangement with the Textile Product Development Laboratory of Owens-Corning Fiberglas Corporation.* This laboratory reports that clothing made from Beta fabric can be washed repeatedly without shrinkage or damage.

2. Wonder Shield - plain. This is a new cloth, woven, coated, and sold by J. P. Stevens. Two samples, one light blue and the other one beige, were supplied to us by

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*See list of addresses in the Appendix.

Mr. Paul D. Motzenbecker of J. P. Stevens. Although this fabric is sold primarily as mattress ticking, it could undoubtedly also be used to cover pillows, to make some types of clothing, and for other purposes.

The advantages of Wonder Shield over the uncoated Beta Fiberglas cloth are that (a) the coatings make it easy to wipe off the surface of the cloth and (b) the coatings prevent linting of the glass fibers. The disadvantage is that the coatings will burn in oxygen or oxygen-enriched air if heated to a high enough temperature, whereas the uncoated Beta cloth is completely non-combustible.

A vertical strip, 12 mm wide, of Wonder Shield held tightly at the lower end by the Chromel wire grid, did not ignite even after one minute's contact with the glowing wire in 100% oxygen at a pressure of 2 atm. abs. However, when a small piece of Scotch tape was attached to one end of the sample and ignited, the flame from the tape set the coatings on fire under certain conditions. In 100% oxygen at either 1 or 2 atm. abs. pressure, the flame was hot enough to partially melt the sample. This weakened the unburned portion of the glass cloth, so that it could easily be torn when cold. At a pressure of only 3 psia in pure oxygen, the coatings could still be set on fire, but the flame was not hot enough to weaken the residual strip appreciably. In 50% O_2 the coatings could be set on fire, but again the flame was not hot enough to greatly weaken the strip. Even in 25% O_2 the coatings could still be ignited, although the flame rate was only 1.8 cm/sec at 1 atm. abs. In compressed air the coatings were not ignited by burning Scotch tape, even at 200 fsw (104 psia).

Mr. Motzenbecker has informed us that on one side the Wonder Shield - plain has an acrylic polymer backing (about 2-1/2% by weight of the fabric), and on the other side the fabric has a silicone "topping," also about 2-1/2% by weight. Thus altogether about 5% of the fabric consists of combustible material. We have not measured the total heat of combustion of the fabric.

Conclusion. Since the Wonder Shield coatings can be ignited in either 100% oxygen or in oxygen-enriched air, anyone contemplating the use of Wonder Shield should himself test for flame-resistance a sample under the conditions of the proposed use. Undoubtedly, uncoated Beta Fiberglas cloth is safer.

Caution. Wonder Shield is sold also in another form, namely, coated with Fasslon "G." This coating is much heavier (about 50% by weight of the fabric), and the Fasslon is readily combustible, even in air at ordinary pressure. Unfortunately Fasslon is transparent and colorless, and the

Fasslon-coated cloth cannot be distinguished in appearance from the plain Wonder Shield.

B. Teflon TFE Fluorocarbon

This is a polymer of tetrafluoroethylene. It has been familiar to chemists for many years as a chemically inert material manufactured by DuPont in plastic and fiber form.

1. Woven Teflon Cloth. Cloth woven of Teflon fiber is available in many different patterns. The natural color of this cloth is dark brown, but it is also avaiable in white. According to the DuPont Company [50], brown Teflon fiber contains about 7 wt-% of carbonaceous residue from the polymerization process. This carbonaceous matter is removed when the white fiber is produced. The purification process makes the white Teflon considerably more expensive than the brown.

Samples of both brown and white Teflon cloth were supplied to us by Stern and Stern, Hornell, New York. The pattern numbers, the approximate weight per square yard, the approximate price per linear yard, and the width of the fabrics, were:

Brown, Pat. No. T3-42, 8.3 oz/yd^2, $16/yd, width = 42 inches
White, Pat. No. T160-42, 9 oz/yd^2, $28/yd, width not known

We cut the samples into strips 12 x 160 mm and tested them. The results are given in Table 12. Linear burning rates below about 2 cm/sec are sufficiently low so that, if they are no higher in a real fire, there would probably be time to extinguish the flames.

Except at 1 atm. abs. of 100% oxygen in the vertical position, where the white cloth is clearly superior, the differences in the burning rates (Table 12) between brown and white Teflon are so small as not to be highly significant.

In the air of the room we were unable to ignite a strip of brown Teflon cloth with the flame of a match; the fabric charred, shriveled, and smoked, but it did not produce a bad odor. Inside the vessel, at a temperature of 1100°F or more, the Teflon was ignited when the air pressure was 100 fsw (59 psia) or higher, but not at atmospheric pressure. Upon ignition, a small blue (and apparently relatively cool) flame was produced which persisted only in contact with the hot igniter. When the closure of the pressure vessel was removed, no unpleasant odor was noticed.

We determined the heat of combustion of various Teflon samples and found it to be 800 to 1200 calories per gram. We also

found that a sample of cotton broadcloth had a heat of combustion of 3760 calories per gram, or about four times that of Teflon.

The ignition temperature of brown Teflon cloth is in the range 1100° to 1200°F (see Table 15). We have not measured the ignition temperature of the white cloth, but it would certainly not be any lower. Results of separate burning tests on brown Teflon are given in Table 13.

Information from the DuPont Company indicates that upon heating at 545°F or above, Teflon can give off vapors which, upon prolonged breathing in sufficient quantities, can be temporarily toxic to man. However, there should be no source of heat that would produce this temperature in a diving chamber.

In view of the high ignition temperature, the relatively low heat of combustion, and the low burning rate (even in pure oxygen), we conclude that either brown or white Teflon cloth has excellent fire-resisting properties.

So far as we know now, Teflon is the only organic polymer from which cloth fabrics can be made, in this highly fire-resistant class. According to results reported by Huggett and his associates [31], Kel-F is highly fire-resistant, but we do not know of any cloth made of Kel-F.

Some information on the thermal decomposition of Teflon was given in Section IV under "A, "The Roth Review." Stern and Stern [24] state: "Teflon cloth can be laundered, but the wearing quality is not as good as that of nylon, Dacron, or Nomex cloth." Teflon cloth can be sewn with Teflon thread, thus avoiding the use of flammable thread.

2. Teflon-Coated Glass Cloth

This is sold by the DuPont Company under the name "Armalon TFE-Fluorocarbon Resin Coated Glass Fabric," and is available in various weights. Samples were supplied to us by DuPont. This material has the advantages that (a) it has a smooth finish which can be easily wiped off, and (b) no glass fibers protrude through the Teflon coat. The only obvious disadvantage is that the heavier weights of fabric are not very pliable, i.e., they tend to be somewhat stiff. The lighter weight (0.03 mil thick) was quite pliable; it has not yet been tested, but will probably prove to be about as fire-resistant as the heavier material which we tested. According to DuPont the glass fibers used to weave the cloth are lubricated with starch in some lightly tinted constructions, and with a silicone lubricant in a

white fabric. We have not yet investigated the effects of these lubricants. The silicone-lubricated fabric supplied to us by DuPont gave excellent results (Table 14). Our tests placed it in Class 8.

C. Asbestos

While the writing of this report was being completed (March, 1967), the Development Laboratory of Uniroyal Fiber and Textile Division sent us three experimental samples of a new fabric which they designated D67054. This fabric was woven from about 90% asbestos fiber, with some Nomex and a little Beta Fiberglas. One sample had no coating, whereas the other two were treated with different weights of silicate.

None of these samples burned in 100% oxygen at 1 atm. abs. pressure, either in direct contact with the glowing Chromel wire alone, or when attempts were made to produce ignition by applying Scotch tape and igniting the tape by means of the hot wire. These samples are therefore in Class 9 (nonflammable).

We made a quick test for wet strength of the three materials. A sample of each of them was soaked in water for 15 minutes. Attempts were then made to pull the fibers apart. The fibers of the untreated material separated readily, but fibers of the other two materials stayed in place when a 100 g weight was applied to a wire hooked through the fabric. It is not known what longer soaking would do to the silicate coating, but the combination of (a) non flammability, (b) porosity, (c) excellent dry strength, and (d) at least reasonable resistance to moisture, makes it possible to consider the silicate-coated fabric as material for uppers for gym shoes to be worn in diving chambers.

D. Avceram CS

An account in Chemical and Engineering News [3] stated that FMC Corporation is developing "silica-carbon fibers by firing cellulose-silica filaments in a reducing atmosphere; the cellulose simply carbonizes." The fibers are porous (ca. 27 m^2/g surface area) and electrically conducting.

A sample of this material, labeled Avceram CS, was supplied to us by FMC Corporation. We found that, even in 100% oxygen at two atm. abs. pressure, no flame was produced, although the sample strip did smolder slowly all the way. The cloth may therefore be considered highly fire-resistant under conditions ordinarily encountered in diving operations (or by NASA). However, the carbon in the sample was found to

color human skin on contact; this somewhat limits possible applications. Possibly the property of electrical conductivity might be useful, or the fabric might be used in the air filter system.

XII. OTHER CLOTH FABRICS

These fabrics have been tested on a small scale for fire resistance and have tentatively been assigned to one of the classes described in Part D of Section I, "Summary and Conclusions." A complete list of manufacturers and/or suppliers, with addresses, is given in Part D of Section XX below.

For data on ignition temperatures, see Table 15. In the case of those fabrics which tend to burn at a medium or fast rate in compressed air, the ignition temperature showed a downward trend as the pressure was increased, but in the case of Nomex, which burned only at a very low rate, the ignition temperature did not change much with pressure.

For data on burning rates, see Tables 16-18.

In order to avoid repetition of the supplier's name, most of the information is given by supplier in alphabetical order. Arrangement by class is to be found in Table 1.

Unless otherwise mentioned, all tests were made on sample strips held in the vertical position; the oxygen diluent, if any, was nitrogen.

It must be recognized that all classifications are tentative, pending confirming tests and/or further experience.

A. Open Market

1. Cotton (Class 1). White cotton terry cloth (8.1 oz/yd^2) and a white light-weight cotton broadcloth (3.1 oz/yd^2) were both tested. The terry cloth was tested just as received from the retailer via the U.S. Navy Experimental Diving Unit. The broadcloth was a part of a shirt which had been laundered many times before it was cut up into samples for the burning tests. Both the broadcloth and the terry cloth burned too rapidly in the vertical position to give rates that could be measured in our equipment, even at atmospheric pressure. In the vertical position, the fuzz (nap) rapidly burned off the terry cloth; meanwhile, the main body of the cloth burned at a somewhat lower rate. At 45° the nap did not flame up, and the burning rate could be measured; this burning rate for terry cloth

turned out to be lower than for the light-weight broadcloth.

Data on ignition temperatures are given in Table 15, and on burning rates at 45°, in Table 16. Burning rates in the vertical position were not measured because the rates were too high.

2. Wool (Class 2). A sample of white wool cloth (8.8 ox/yd^2) was purchased at about $2/yd at a department store. When a strip of it was hung vertically in the air of the room and ignited at the bottom, it burned slowly with a slightly smoky flame as long as the flame of the burning wool stayed directly below the unburned wool. Combustion of the wool gave a nauseating and somewhat irritating odor. The burning wool strip tended to curl at the bottom so that the flame was no longer below the remainder of the strip; when this happened, the flame went out. Strips of wool pinned in the usual way onto the sample holder and inserted into the pressure vessel in a vertical position in air, burned slowly and completely at all pressures up to 148 psia (300 fsw).

When a strip of wool was mounted at an angle of 45° and ignited in compressed air, the flame usually went out, because at this angle the flame had difficulty in bringing the unburned wool to the ignition temperature. Even when the flame did not go out, it climbed only very slowly.

Wool is safer in compressed air than untreated cotton because it is more difficult to ignite and burns more slowly, but a wool flame is not self-extinguishing when the sample is held in the vertical position, even in air at only one atmosphere pressure.

For ignition temperatures see Table 15; for burning rates seen Tables 16 and 17.

B. American Brattice Cloth (ABC)

Brattice cloth is customarily used in mining for the control of dust or ventilation. The cloth is usually treated to make it fire-retardant.

The most flame-resistant material sent us by ABC was "Navy Brattice Cloth," (Class 6) used aboard ships to provide a protective cover over fiber glass insulation. The following information was given [42]: "Navy Brattice Cloth is a cotton Osnaburg construction with a yarn count of 24 warp by 20 fill yarns per square inch. The untreated weight is approximately 10 ounces per square yard and we add roughly 20%, making the total of finished weight about 12 ounces per square yard. Our flameproofing is basically an ammonium phosphate solution with certain additives to keep it a neutral pH, and it is water soluble." The price is approximately 49 cents/yd^2.

Linde findings were:

1. Air. At atmospheric pressure the cloth burned only in contact with the igniter; the flame then went out. At 200 fsw the sample flamed only in contact with the igniter but smoldered part of the way up the strip.

2. 25% oxygen. At atmospheric pressure the result was the same as at 200 fsw in compressed air. At 200 fsw in 25% oxygen, a feeble flame crept up the strip, and the strip smoldered part way up from the igniter.

3. 31% oxygen. At atmospheric pressure a small, erratic flame slowly consumed the strip. At 200 fsw the strip burned much faster; when the flame went out, the residue of the strip smoldered until the sample was consumed.

This is the most flame-retardant cotton we have yet tested. The appearance is similar in color and texture to that of burlap.

Other samples supplied by ABC:

Plastic-coated jute. Uncoated brattice jute would probably be in Class 5 or 6, but could not be washed or wiped off. The clear plastic coating on JP No. 1 and JP No. 2 burned readily, and hence the coated fabric is in Class 0.

Polyvinyl chloride (PVC) cloth. One type, 20Y, had no reinforcing. Another type, 12NP, consisted of PVC reinforced with nylon fabric. This cloth is said to be "very durable" [and] "can be used over and over." Both of these PVC fabrics are in Class 3. The surface is smooth and could easily be washed off.

C. Celanese Corporation

It is known that this company developed, under an Air Force contract, a polybenzimid azole fiber. Cloth woven from this fiber is called PBI, and one of its proposed uses was to make parachutes that have to withstand the extreme heat of re-entry from space.

D. Dow Badische Company

This company makes Rovana fabrics, the composition of which has been previously mentioned in part J (National Conferences) of Section IV, the literature survey.

Three fabrics were purchased from Schlosser Textile

Company. All were 48 inches wide. Descriptions were as follows:

Pattern No.	Color	Price/linear yd	Composition, %			
			Rovana	Verel	Rayon	Flax
5700	beige	$1.50	39	38	16	7
6400	flax	1.65	32	43	18	7
5800	beige*	2.00	38	31	22	9

*silver-gray PVC coating on one side only

Strips of the first two of these fabrics behaved the same way when tested. In the air of the room, in contact with a flame, they rapidly shriveled, charred, and smoked, but did not catch fire for more than a moment. In 25% oxygen the samples smoked, charred, and shriveled but did not ignite at 0 fsw, but at 100 fsw the samples burned with a medium-sized flame, (i.e., not a small flame that hugged the sample). In one case a burn rate of 3.6 cm/sec (vertical) was measured, but in the other cases it was not possible to read clear burn rates from the recorder chart.

These Rovana fabrics are sold chiefly as curtain material. They are strong and attractive. The third material was Rovana coated on one side with PVC. A sample of the coating was separated from the substrate and tested separately. In the air of the room, a vertical strip of the coating burned with a flame while in contact with the flame of a match, but was self-extinguishing when the match flame was withdrawn.

Both the coating and the substrate shriveled, charred, and smoked in contact with the match flame. In 25% oxygen at 0 ft the sample enflamed at the grid, but the flame was self-extinguishing within 2 cm of the grid. It was obvious that the more flammable part of the fabric was the coating. The coating, however, gives a smooth finish which could easily be wiped off to keep the surface clean. This material might therefore have some value as a mattress or pillow cover if the percentage of oxygen were not over 25%, and if the total pressure were not much over atmospheric.

A recent news item [2] indicates that Dow Badische is discontinuing the manufacture of Rovana.

E. Dow Chemical

Dow manufactures and sells a compound referred to as APO, which can be used for making cotton cloth flame-retardant.

For a description of APO, tris(1-aziridinyl)phosphine oxide, see part M of Section IV above.

Although Dow does not sell APO-treated fabrics, the company supplied us with a sample of treated cotton sateen from its laboratory. This sample was assigned to Class 3. See "Caution" in Part F of Section I, "Summary and Conclusions."

F. DuPont

TFE Teflon and Teflon-coated glass cloth were described in the preceding section.

Nomex "high-temperature resistant" nylon fiber. A sample (4.5 oz/yd^2) of natural (white) color cloth woven from this fiber was supplied to us by DuPont. When a strip of this material was hung in the air of the room, it did not ignite (except momentarily) when either a burning match or the flame of a lighter was held to it. The Nomex in contact with the flame just shriveled and charred.

In the pressure vessel, by use of the Chromel igniter, it was possible to start the Nomex burning in air because the igniter can be brought to a temperature higher than that of a match or lighter flame. At atmospheric pressure the flame was self-extinguishing, but at pressures in the range 26 to 148 psia (25 to 300 fsw), the fabric usually burned slowly (at a rate of less than 1 cm/sec) all the way to the top, although occasionally the flame went out. In all cases the flame appeared small and weak, and had the appearance of coming from only a portion of the width of the fabric. The DuPont Company has pointed out to us that our results with Nomex might have made it appear safer if we had tested the strips of cloth while they were hanging loosely in the vertical position instead of being mounted on the sample holder. In the loose condition the Nomex, when ignited at the bottom, tends to shrink from the flame and extinguish itself. In 25% oxygen (Table 18) the Nomex burns slowly all the way from 0 to 300 feet, indicating that Nomex has a safety factor (for use in air) and can probably be recommended for use in compressed air at all pressures from 0 to 300 feet. Details of the results with Nomex cloth are given in Tables 15-18.

A sample of terry-knit Nomex Cloth was also supplied to us by DuPont. Test results for this are given in Table 19. Since this material did not burn rapidly in 25% oxygen, it will be tested at higher oxygen percentages when time permits. In 25% oxygen at pressures from 0 to 200 fsw, the nap did not flare up the way the nap on ordinary cotton terry cloth does. According to DuPont, the presence of the nap somewhat increases the water-absorbing power of the Nomex cloth.

When the closure of the pressure vessel was removed after a sample of Nomex had been burned, there was left a faint, not unpleasant odor.

According to information supplied by the DuPont Company [4], clothing made of Nomex generally outlasts comparable cotton fabrics by a factor of 3 to 5. Nomex appears to be less easily stained and more readily washed than cotton. Combustion of Nomex yields water vapor and carbon dioxide; some carbon monoxide is produced when Nomex is pyrolyzed, or when it is burned in a deficiency of oxygen. Other than this possible production of carbon monoxide, DuPont's Haskell Laboratory for Toxicology and Industrial Medicine found no toxic products during pyrolysis or combustion.

Nomex has one problem in common with a number of other synthetic fibers: static electricity may be generated when the fabric is handled. If readily flammable materials have been eliminated, small sparks, if any, from the Nomex would do no harm, but in case the possibility of static spark formation is of concern, the DuPont Company has supplied the following information:

"There is no known permanent antistatic treatment; however, there are treatments which can be reapplied during each washing. To control static, it is suggested that 4% [Ethoquad C-12*] be applied in the final rinse water after the garments are washed." This treatment is supposed to make Nomex even more antistatic than cotton.

It appears that Nomex cloth might be used in making gowns, bed sheets, etc., for use in chambers containing compressed air. Although Nomex can be ignited by application of a high temperature, it burns so slowly, even when the air is enriched to 25% oxygen, that the flame could probably be extinguished before much harm is done.

A better opinion of the safety of this cloth will be available after larger-scale fire tests, to be made in the coming year, have been completed.

The current price of Nomex cloth is of the order of $6 per square yard of the 4 to 5 oz/yd^2 weight.

Nomex is also available in the form of carded batting that can be used as pillow stuffing. The batting is soft and resilient. There is also a batting material called Havolite which is made of 85% Nomex + 15% Vinyon fiber. Preliminary tests for flame resistance indicate that the fire resistance of these materials is about the same as that of Nomex cloth.

G. FMC Corporation

A sample of Avceram RS, an experimental fabric, was given to us. It fell into Class 1. After the RS is heated,

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*Made by Armour Industrial Chemical Company

it changes to Aversan CS, which as previously mentioned, is in Class 8.

H. Hooker Chemical Corporation

1. Treated wool (Class 4). A sample of wool cloth was treated by Hooker with tetrakis (hydroxymethyl)phosphonium chloride (THPC). This was an experimental sample and had been given Hooker's "Finish No. 4."

The cloth was ignited by the hot wire, but the flame was self-extinguishing in compressed air at pressures up to 100 fsw. In 25% O_2 the sample did not burn at 0 and 15 fsw, but the entire strip burned at 20 fsw and at higher pressures.

2. Roxel. Several samples of Roxel were given to us by Hooker. Roxel is the trade name for cellulosic fabric finished with tetrakis (hydroxymethyl)phosphonium chloride (THPC) in a proprietary system developed by Hooker, based on work originally done [47] at the Southern Regional Research Laboratory of the U.S. Department of Agriculture (see Part M of Section IV above). The flame-retardant finish is said to withstand repeated laundering. Roxel fabric is commercially available at prices slightly higher than those of cotton.

When the flame from a match (or cigarette lighter) was brought in contact with the lower end of a strip of Roxel held vertically in the air of the room, the fabric burned while being heated by the flame, but combustion stopped as soon as the match or lighter was withdrawn. During the burning, the Roxel gave off irritating fumes, the nature of which is discussed in Part M of Section IV, above. We tested two samples of Roxel (cotton). For details of the results, see Tables 15-18. The broadcloth weighed about 3.1 oz/yd^2, and the Worklon about 10.2 oz/yd^2. See "Caution" in Part F of Section I, "Summary and Conclusions."

J. Mine Safety Appliances

This company gave us a fire-retardant wool blanket, Part No. 04-12487, and advised that the fire-retardant treatment is not resistant to laundering; it will wash out in water. In dry cleaning there would also be some (unknown) loss in fire-retardant properties, so it would be desirable to re-treat the blanket after every cleaning to ensure maximum protection.

Our tests indicate that this blanket belongs in Class 4. If larger-scale tests confirm this classification, the blanket might be useful in hyperbaric chambers filled only with compressed air. See "Caution" in Part F of Section I, "Summary and Conclusions."

K. J. P. Stevens

Both J. P. Stevens and Owens-Corning supplied us with samples of Wonder Shield - plain and Wonder Shield coated with Fasslon "G." The plain material is highly resistant to ignition, whereas the Fasslon coating burns readily, even in air at atmospheric pressure (Class 1). These materials have both been described in Section XI above.

L. Union Carbide Corporation

Dynel is a modified acrylic ("modacrylic") fiber described briefly in Section IV under "J - National Conferences." It is manufactured by Union Carbide Corporation.

Three samples of different types of Dynel cloth supplied to us by Uniroyal, Inc. (Formerly U.S. Rubber Company) were tested in the usual way.

Dynel has a high ignition temperature in air (1000° to 1200°F) and a considerable amount of natural flame-resistance brought about by its high chlorine content. Even when a strip of the cloth was exposed to the Chromel wire igniter at or above the ignition temperature, the cloth often did not ignite, because the Dynel shrank from the hot wire. (Dynel has the characteristic of shrinking rapidly away from a source of heat.)

Dynel will burn, even in air at atmospheric pressure, if sufficient heat is applied, but the material seems to have a low heat of combustion (not measured by us), and appears, on the basis of small-scale tests, to be potentially useful, even in 25% or 30% oxygen. It is planned to test larger samples in a much larger vessel during the coming year.

Following are a few results obtained on a small scale (6 to 12 mm wide strips of the cloth). Designations are those given by the Textile Division of Uniroyal.

Dynel Cloth Type 907 (Class 5). A strip at a 45° angle in air at 14.7 psia ignited after 10-second contact with the glowing wire to give a small, bright flame that almost immediately went out. The strip was damaged only within 0.5 cm of the igniter. In a repeat test, the small flame was sputtering and yellow; the strip was burned within 1 cm of the igniter grid. Results were essentially the same at a pressure of 300 fsw.

All other tests in compressed air were made in the vertical position. In all cases, including the test at

300 fsw, damage to the strip was confined to a distance of less than 4 cm from the igniter. The flame always extinguished itself within 2 seconds, a short distance above the igniter.

In 25% O_2 the sample was self-extinguishing at 1 atm pressure, but at 100 fsw the whole strip burned, and at 200 and 300 fsw the strip burned more rapidly.

Dynel Cloth Type 907F (Class 5). In air at 0, 100, and 200 fsw the sample was self-extinguishing. In 25% oxygen, the strip was ignited at 100 fsw after 20 seconds, but the burning was interrupted by apparent melting and shrinking. At 200 fsw, the strip ignited after giving off sparks on the glowing Chromel wire. The strong flame seemed to melt the strip above the flame. A little of the molten material clung to each pin on the sample holder, where it continued to burn: on one pin the flame was quite large. After the flames went out, smoldering continued for a short while.

As with other synthetic fibers, there is a static electricity problem with Dynel. Considerable progress has been made in recent years in overcoming this problem. For example, information from Union Carbide indicates that the addition of 0.5% of Tergitol non-ionic NPX in the final rinse water after laundering is effective in eliminating static until the next laundering.

Olive Colored Dynel Tent Material - No Number. Self-extinguishing in air at 0, 100, and 200 fsw. In 25% oxygen at 0 fsw, the flame was self-extinguishing within about 3 cm of the igniter grid. Even at 100 fsw the flame was self-extinguishing. In 30.9% O_2 at 0 fsw in two tests, no ignition took place. After the experiments, the strips were examined and found to be charred and curled a distance of 1 cm from the igniter wire grid.

Dynel Blankets. These blankets are warm and attractive. No sample has so far been tested, but if the blanket material is as fire-resistant as other types of cloth that have been tested, it will be in Class 5 (or possibly Class 6). In the past, the problem with Dynel blankets has been the generation of static electricity in dry atmospheres. This problem apparently has now been largely overcome, and we are planning to make tests during the coming year.

M. Uniroyal Fiber & Textile Division of Uniroyal, Inc. (formerly U.S. Rubber Company)

One of the interests of Uniroyal's Textile Division is the sale and development of asbestos-containing fabrics.

Like glass, asbestos itself is completely non-flammable, but cloth woven only from asbestos fibers is weak and lints badly.

In order to produce an asbestos cloth that has any appreciable degree of strength, it is necessary to use a yarn of some stronger fiber as part of the woven fabric. Among the stronger fibers which have been used in the past are cotton, polyester, nylon, Dynel, and Beta Fiberglas.

To produce an asbestos cloth that does not lint, it is necessary to apply a coating of some kind. Some of the coating materials used in the past are organic resins, PVC, and aluminum in neoprene.

It has already been mentioned that recently (March 1967) the Development Laboratory of the Uniroyal Fiber & Textile Division developed a new type of non-flammable (Class 9) cloth made chiefly from asbestos.

Previous to the preparation of this new type of cloth, Uniroyal gave us samples of Dynel cloth (see above under Union Carbide Corporation) and of various asbestos-containing fabrics. Following are the results of some of our tests.

Style S/1445 Asbeston (Class 6). Composition: 77% asbestos, 23% Dynel. Weight: 1.4 lb/yd^2.

Since this fabric has no coating, it tends to lose asbestos fibers slowly by linting.

The fabric was tested only in 30.9% O_2. At 0 fsw the sample did not ignite; at 50 fsw the sample ignited on the grid and then extinguished itself; at 100 fsw, the flame lasted for a few cm, then extinguished itself, but continued smoldering until the Dynel was mostly burned. At 200 fsw the burning and smoldering were more rapid.

Style S/3620-IAR Asbeston, barbecue mitten and ironing board cover (Class 6). Composition of main fabric: 82% asbestos, 18% polyester. Coating: acrylic type, about 2% of the weight of the fabric. Weight: 0.80 lb/yd^2

This fabric has a thin, transparent acrylic type coating on both sides to prevent linting of the asbestos.

In pure oxygen at 3 psia the organic matter in the specimen burned the entire length of the sample. A rate of 1.6 cm/sec was measured. In 7.5 psia the rate was 3.5 cm/sec. In 1 atm. abs. the rate could not be measured because the flame was too high and therefore preheated the upper thermocouple. In all cases, the asbestos was left as

an intact strip after combustion was complete.

In air at 200 fsw and in 30.9% O_2 at 0 fsw the organic surface coatings were apparently not completely burned, as the sample strip after combustion still felt much as it did at the beginning. The flame rate in 30.9% O_2 at 0 fsw was 1.8 cm/sec; at 100 fsw the flame was hotter and the organic matter was apparently completely consumed.

Style S/5670-FEL Asbeston, barbecue mitten (Class 5). Composition: about 80% asbestos, about 20% carrier fiber (mixture of nylon and polyester), coated on one side only with a thin coating of a flame-retardant aluminum-pigmented latex. The other side seemed to be entirely uncoated.

We tested this fabric in compressed air and in 24.6% O_2. In compressed air the strip was ignited and seemed to burn quite rapidly on the underside. However, when the remaining material was examined, combustion on the underside extended to only 2 cm from the igniter, and from that point, another 7 cm along one edge. At 200 fsw, combustion was more complete.

In the 24.6% oxygen gas mixture, at 0 fsw the underside (uncoated side) burned with a flame 3 to 4 cm high, but the strip was still quite strong when the flame had run up the entire strip. At 100 fsw again only the uncoated side burned; a flame rate of 1.2 cm/sec was measured. At 200 fsw, the underside was badly charred when the flame had run along the entire strip.

The interesting thing about these results is the protection the aluminum layer seemed to offer. No flame was observed on the aluminized side of the sample in any of the tests.

Basic Style S/6555 Asbeston, 80% asbestos + 20% polyester (Class 5).

One sample, F-3339-A, coated on on side only with pink PVC containing a flame-resistant plasticizer. A second sample, F-3339-B, coated on both sides with pink PVC which did not contain the flame-resistant plasticizer. (The F numbers are Uniroyal development numbers.) The PVC coating stops all asbestos linting and makes it possible to wash the fabric on the coated side(s).

Both samples were self-extinguishing in compressed air, even at 200 fsw. In 25% oxygen, neither sample was successfully ignited at 0 fsw. At 50 fsw sample Type A (with flame-resistant plasticizer) was self-extinguishing, but all (except the asbestos) of Type B burned. At 100 fsw both samples burned. There was actually very little

difference in behavior between the two. In 30% O_2 at 0 fsw Type A burned readily; Type B was not tested.

N. Wheeler Protective Apparel, Inc.

Several different Wheeler fabrics were furnished to us.

No. 35. Silvrprened Fiberglas (Class 6). This is a light-weight glass cloth coated on both sides, according to Wheeler, with pigmented neoprene. This pigmentation gives the cloth a silvery-gray appearance. We analyzed the coating and found that the silvery sheen is probably due to metallic aluminum. Titanium was also present, probably as the dioxide, TiO_2. The cloth is pliable, has a smooth surface, and looks as though it could easily be wiped off.

No flaming took place (a) in 25% O_2 at 100 fsw, (b) in 31% O_2 at 0 fsw. Time did not permit making tests at higher partial pressures of oxygen. This material is quite promising and further tests will be made during the second year of the contract.

No. 12 Underwriters' Grade Basket Weave Asbestos (Class 5). This heavy cloth consists of 83% asbestos and 17% cotton. The material, according to Wheeler, is treated to reduce lint, to give it more tensile and abrasive wear resistance, and to flameproof the cotton content. [The fabric did not look as though the surface could easily be washed off.]

Self-extinguishing in 25% O_2 at 0 fsw. Not tested in 30% O_2. In 40% O_2 at 0 fsw all the cotton in the strip apparently burned.

No. 61 Khaki (Class 5). This is a cotton fabric which has been "permanently flameproofed."

Self-extinguishing in compressed air up to 300 fsw. Self-extinguishing in 25% O_2 at 0 fsw, but burned rapidly at 200 fsw.

No. 60 Green (Class 3). One sample, No. 60 Wheeler green cotton, fell in Class 3, whereas Wheeler No. 61 Khaki was apparently in Class 5. We do not know whether these differences are real, or were caused by the fact that the available samples were too small for making the usual tests. See the "Caution" in Part F of Section I, "Summary and Conclusions."

XIII. ELASTOMERS AND FLEXIBLE TUBING

At the present time, rubber face masks are used in Navy diving chambers for the administration of oxygen.

Strips cut from a rubber mask supplied by the U.S. Navy Experimental Diving Unit, burned readily in air at atmospheric pressure. An effort has therefore been made to procure samples of fire-resistant rubber from which masks could be made.

The best materials received to date are (a) an experimental rubber from Thiokol; the sample did not burn, even in 100% oxygen at 2 atm pressure, and (b) DuPont Viton for gaskets, and (c) DuPont Hypalon as a possible rubber for masks.

Although DuPont Teflon is not an elastomer, it can be made by corrugation into highly flame-resistant flexible tubing. Flexible tubing can also be made out of either annular or helical corrugated metal tubing or of uncorrugated Teflon covered with metal braid. Most of the details are given under the manufacturer's name, and some under the heading "Flexible Tubing," below.

For all test results given in this Section, sample strips were held in the vertical position unless otherwise indicated.

A. Dow Corning

This company sent us two samples: a molded ASTM Slab of Silastic S-2316U flame-retardant silicone rubber, Lot No. 6689, and recently, a piece of glass cloth coated with the same kind of Silastic. Tests on the glass cloth have been begun; it is at least in Class 6. The properties of the Silastic slab, as reported by Dow Corning, are:

Color	Off-white	
Specific gravity	1.52	
Molding temperature	260°F	
Brittle point	Below -100°F	
	4/392°F	24/480°F
Durometer, Shore A	65	77
Tensile, psi	700	860
Elongation, %	200	70

The slab was formulated with 1% Luperco AST.

The flame retardance measured by Dow Corning on calendered glass cloth coated with the Silastic, in accordance with Federal Specification CC-T-191b, Method 5902 [see part N of Section IV, Survey of the Literature] was:

	4/392°F	24/480°F
Flame out time, sec	5	3
Glow out time, sec	1	0.5

Tonawanda tests on the slab:

Compressed air

0 fsw — It took 20 sec contact with glowing wire to ignite. Self-extinguishing beyond igniter.

100 fsw — Slow to ignite. Burned slowly at first, but the flame grew as the Silastic became hot, and finally consumed the whole sample.

25% O_2

0 fsw — Self-extinguishing within 1 cm of igniter wire.

100 fsw — About the same as for 100 fsw of compressed air.

B. DuPont

DuPont literature lists five synthetic rubbers. Of these, Adiprene, a urethane rubber, and Nordel, a hydrocarbon rubber, were not recommended for our application. Samples of the other three were supplied.

1. Neoprene (M-5550). Black sheet, 1/32 inch thick. We found this to be in Class 1. It burned in air at atmospheric pressure.

2. Hypalon (Fairprene 70-001) (Class 3). Black sheet, 1/16 inch thick. According to the DuPont Company, it may be possible to make gas masks from Hypalon, but apparently this has never been tried.

3. Viton (Fairprene 80-001) (Class 6). Black sheet, 1/16 inch thick. Viton is expensive; for example, the cost of one square yard of glass cloth coated with 0.015 inch of Viton is about $25 [56]. The principal use of Viton in hyperbaric chambers will probably be in making gaskets.

C. Flexible Hose and Tubing

Although Teflon is not an elastomer, it can be made into flexible tubing by corrugation. Such tubing is for sale, for example, by Pope Scientific, Inc., 13600 W. Reichert Avenue, Menominee Falls, Wisconsin, 53052. The bend diameter

of the currugated tubing is said to be one-half of the I.D. of the tubing, and the tubing is said to withstand continuous flexing. A typical price from a recent catalog is $2.90 per foot for the 1/4 inch I.D. tubing.

Flexible, high-pressure hose made of Teflon (not corrugated) covered with metal braid is sold by a number of companies, including the following:

Anaconda Metal Hose Division
Anaconda American Brass Company
Waterbury, Connecticut

Resistoflex Corporation
Roseland
New Jersey

EverFlex Products, Inc.
P.O. Box 210
Chicopee, Massachusetts 01044

None of this tubing has been tested by us, but Teflon has been tested, as mentioned elsewhere, and the stainless steel braid would probably not burn, even in a gas mixture containing 50% oxygen, unless the pressure were extremely high.

A recent Anaconda Metal Hose catalog states: "Teflon hose has excellent fatigue characteristics and extremely long service life under most conditions." It has a wide useful temperature range: -65° to +450°F.

The companies named above also list all-metal flexible high-pressure hose made of either annular or helical corrugated metal. No sample of this hose has been tested by us.

D. General Electric Co., Silicone Products Department

This company supplied two samples, SE-9029 and SE-9044, of flame-retardant silicone rubber. These seemed, in our tests, to be equally flame-retardant. G. E. recommends SE-9029 for use in making face masks or flexible tubing. Some of the properties listed by G. E. for SE-9029 are:

Property	Press cure, 10 min/275°F	After heat aging 24 hr/480°F
Hardness, Shore A	50 ± 5	60 ± 5
Tensile strength, psi	1550	800
Elongation, %	600	200

In our tests, in air both at atmospheric pressure and at 25 fsw, the samples were difficult to ignite and were self-extinguishing when the ignition source was turned off. At a pressure of 100 fsw the samples burned slowly but completely; SE-9029 had a bright yellow flame. At 300 ft the SE-9029 sample was in contact with the glowing igniter 10 seconds before combustion started. In 25% oxygen, the flames were self-extinguishing at 0 fsw, but the samples burned completely at 100 fsw. No tests were made at intermediate pressures.

E. B. F. Goodrich Industrial Products Company

This company has sent us an experimental sample of flame-retardant rubber, but the sample was received too late for testing before this report was issued.

F. Minnesota Mining and Manufacturing Company

This company manufactures two types of flame-retardant elastomers, Kel-F and Fluorel. Samples have been requested but have not yet been received.

G. Thiokol Chemical Corporation, Reaction Motors Division

This company sent us a small sample of their experimental "carboxy nitroso rubber terpolymer." This elastomer appears to be completely non-combustible, Class 9. We carried out experiments with the sample at an angle of 45° and in the vertical position, in 1 atm and in 2 atm of 100% O_2. No flame was produced in these tests. Instead, when the igniter was turned on, the portion of the sample in contact with the hot wire simply disappeared. Apparently the heat pyrolyzed and vaporized the sample. There was no visible combustion of any kind.

We plan to investigate the possibility of making face masks from this new type of rubber.

XIV. ELECTRICAL INSULATION

Selection of insulation for electric wires does not present a serious problem, since some highly flame-resistant types are available. See Table 3 for tentative classifications.

DuPont

This company supplied a length of braided copper wire approximately 1 mm in diameter, designated 019-919, coated with a 7 mil thickness of Kapton polyimide. The coating

was not ignited by the glowing Chromel wire, even in 100% O_2 at 1 atm pressure, and it is therefore tentatively in Class 9; however, in an actual fire, in which the whole wire may be heated to a high temperature, the insulation may be only in Class 7, where the Kapton film itself is. (See Section XVIII below.)

International Telephone and Telegraph Corporation, Wire and Cable Division

This company supplied two types of insulated wire which behaved very differently. In the case of Type AIR, the insulation on both samples burned readily in air (Class 0), whereas the samples labeled WTE were in Class 8. The company's designation for the four samples is:

AIR 1930 U 18 gage, AWG white

AIR 1932 U 20 gage, AWG white

WTE 1930 A 18 gage, AWG white-red-yellow

WTE 1932 A 20 gage, AWG black

XV. FOAMS AND OTHER STUFFING MATERIALS FOR PILLOWS AND MATTRESSES

No highly flame-resistant foam suitable for use in pillows and mattresses has yet been found. The U.S. Navy Experimental Diving Unit is using glass fiber stuffing for both pillows and mattresses; this material should be non-flammable, but we have not yet received any of it for test. DuPont has supplied two types of pillow stuffing material, both of which are probably in Class 5, although we have not yet completed our tests. We have been told by Owens-Corning Fiberglas that Beta Fiberglas is not suited for pillow stuffing because the fibers are too fine; the fibers would break and the pillow would become hard and lumpy.

For tentative classifications see Table 3.

DuPont

This company sent us samples of two kinds of pillow stuffing, (a) Nomex carded batting and (b) Havolite batting. Havolite consists of 85% Nomex and 15% Vinyon.

Our tests on these materials have not yet been completed. Both of them will probably be in Class 4. They should make comfortable pillows.

DuPont tells us that neither Hypalon nor Viton could be used to make a foam pillow because these elastomers are not available in latex form.

Pittsburgh Plate Glass

This is the supplier of the glass fiber pillows and mattresses used by the U.S. Navy Experimental Diving Unit. As mentioned above, none of this material has yet been tested by us.

Reinforced Air Corporation

This company sent us samples of two types of material, neither of which has yet been tested except to ascertain that one of them, called "Isoschaum," does not ignite at all in air--it only chars when a match flame is held to it. Isoschaum is a urea-formaldehyde foam with a density of 0.6 to 0.7 lb/cu ft. Mr. McPherson of this company has expressed some doubt as to whether this foam is strong enough to support a person's body without collapsing.

The other sample given us was a "cushion" which consisted of a double layer of PVC with uninflated bubbles of various sizes built into it. Mr. McPherson has suggested that these bubbles might be inflated with an inert gas.

It is planned to test these materials during the coming year.

Union Carbide Corporation

This company has supplied a sample of an experimental flame-retardant urethane foam No. 584RD69. This would appear to make a comfortable pillow or mattress material. Our tests tentatively place it in Class 2.

XVI. FILM

Only one kind of film has been tested to date, namely Kapton polyimide from DuPont. The three samples supplied to us were as follows:

Type	Thickness	Color	Our Tentative Classification
100H	1 mil	yellow	5
300H	3 mils	orange-brown	7
200F919	1 mil*	yellow	7

*Estimated

All samples were transparent. The film is remarkably fire-resistant. It is not known whether the lower fire-resistance classification for Type 100H is due to the fact that there is actually a difference in composition of the films, or that one sample was thinner than the others.

Some of the properties of the 1 mil Type H film, as given by DuPont are:

Zero strength temperature, 815°C

	25°C	200°C	ASTM Method
Ultimate tensile strength	25,000 psi	17,000 psi	D-882-64T
Yield point	10,000 psi at 3%	6,000 psi at 3%	D-882-64T
Folding endurance	10,000 cycles	-	D-2176-63T
Initial tear strength	510 g/mil	-	D-1004-61
Density	1.42 g/cc	-	D-1505-63T

By coating Kapton film with Teflon, a combination (called Kapton Type F film) is obtained which may be heat bonded (at 500 to 600°F) to itself or to other thermally stable substrates such as metals, glass cloth, etc. without the use of adhesives. The coefficient of linear expansion of Kapton is 2×10^{-5} in./in.°C.* Applications of Type F Kapton make use of "the excellent high temperature electrical and mechanical properties of thin gauge Kapton plus the complete seal, moisture protection, and flexibility imparted by the Teflon," according to DuPont.

A roll of Kapton 100H film costs about $1.66/yd^2.

XVII. PAINT

As mentioned in Part B of Section IV above, an experiment was conducted at the U.S. Navy Experimental Diving Unit in which the flame of a butane torch was applied to a coat of paint on the steel walls of a decompression chamber while the chamber was filled with air at atmospheric pressure. The flame of the torch did not ignite the paint, even though a dried paint film alone could be ignited in air. Moreover, during the disastrous fire of February 16, 1965, the paint on the walls of the chamber did not burn, even though the temperature in the chamber was probably well above 400°C, the pressure about 41 psia, and the atmosphere enriched to

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*Over the temperature range -14°C to +38°C

about 30% oxygen just before the fire.

The best available explanation for the fact that the paint burned in neither the torch experiment nor the fire of February 16, 1965, is that heat was conducted away so rapidly by the thick steel walls that the paint did not reach ignition temperature.

We were asked to explore this matter further. The Experimental Diving Unit supplied us with partly filled cans of the same kind of primer and cover paint as is used in the decompression chambers. Designations for these materials were:

(1) Primer. Heat resistant aluminum primer, Federal Stock No. 8010-815-2692.

(2) Cover Paint. White cover paint, Military Specification Mil.E-179706, 19 September, 1961, Enamel, nonflaming(dry), chlorinated alkyd resin, soft white, semigloss, Formula No. 12458, Federal Stock No. 8010-577-4738.

A. Tests on Paint Films

The cover paint in the can supplied by the Navy had a "skin" over the top. A portion of this white skin, which presumably included some of the chlorinated alkyd resin, was separated from the liquid, dried for several months, and ignited in air at 0 fsw. The ignition temperature was 820°F and the paint film burned slowly (Class 1).

The primer did not have a skin on top.

A brass strip was painted with the white paint and allowed to dry three days. The paint film was separated from the brass with a razor blade. The film burned in the air of the room in tne vertical position, but the rate of combustion was sufficiently low so that this paint was assigned to Class 1 rather than Class 0.

A primer coat and two coats of the white cover paint were applied, with several days between each coat, to a piece of brass. Some time later the brass was bent enough to loosen the paint film, and the latter was stripped off and ignited in the air of the room in the vertical position. The film burned readily; the side with the aluminum primer coat appeared to burn faster than the white side. A self-supporting residue was left.

These experiments left no doubt that the paints, both the primer and the cover paint, were flammable in air at atmospheric pressure, although the cover paint has some flame-resistance.

B. Tests on Lightly Backed Paint Films

(1) Primer

The primer was well mixed and painted on a strip of thin brass shim stock (1.1 cm wide, 17.8 cm long, and 0.0055 inch thick). The coating was allowed to dry for several days. Then it was tested while still on the brass strip. At 186 fsw (142 psia) of compressed air the strip, held in the vertical position, was ignited without difficulty; the flame burned all the way up the strip at a moderate rate. No tests were made at lower pressures.

A strip of the shim stock painted with one coat of primer and two cover coats was tested in the vertical position. At 0, 100, and 300 fsw the paint film was ignited with the hot Chromel wire and burned to a distance of about 2 cm from the wire. The flame then extinguished itself. In view of the experiment described under Part A above, in which the same paint film, when lifted from the brass substrate and ignited, burned readily and completely in air at atmospheric pressure, it is seen that even the very thin (0.0055 inch thick) brass substrate greatly retarded combustion.

C. Tests on a 3/4-inch Thick Steel Block

A carbon steel block 1 in. wide by 1.5 in. long by 3/4 in. thick was prepared by drilling a 1/16-inch diameter hole from one side through the block to within 1/16-inch of the 1 x 1.5 inch surface to be painted. A thermocouple was inserted in this hole to measure the temperature of the steel near the painted surface during ignition attempts.

The primer and two cover coats of the paint were applied, with 16 to 24 hours of drying time between each coat, and 2 weeks' drying time at the end. Attempts were then made to ignite the paint film with a hot Chromel wire spiral held tightly on the film, in compressed air at pressures up to 300 fsw and in 100% oxygen at 2.11 atm. abs. The igniter wire glowed brightly where it was not in direct contact with the block, but glowed only dully where it was in contact with the paint, attesting to the fact that the steel block was conducting heat away from the wire. Wherever the hot wire was in contact with the paint, the latter either softened, allowing the hot wire to make an impression, or produced small blisters. Continued heating caused the raised part of the blisters to char, but the paint film did not ignite. The temperature measured in the thermocouple well reached 50°C.

In an actual fire, paint films on interior objects which are so situated that the entire object becomes hot, might burn,

but paint films on the inside surface of outer steel walls would probably not burn at all as long as the outer walls were not appreciably heated.

Our findings fit in well with results of experiments conducted by Huggett and associates [31] (described in Part F of Section IV above) on the burning of layers of Scotch tape on an aluminum plate one-eighth of an inch thick.

XVIII. REGION OF NON-COMBUSTION

It has been known for a long time that when a candle burns in a closed space filled with air, the candle-flame goes out before all the oxygen in the air is exhausted.

Like a candle, paper, cotton cloth, and other flammable materials burn readily in air at atmospheric pressure. However, in mixtures of oxygen and nitrogen in which the per cent of oxygen is less than it is in air (20.95%), there is undoubtedly some concentration of oxygen below which the combustion of a given flammable material at a total pressure of one atmosphere will no longer be supported. If the mixture which contains the maximum per cent of oxygen which will not support the combustion, e.g., of paper or cotton, is compressed, there will probably be found some pressure at which ignition takes place and combustion is again supported. Thus a curve can probably be drawn for pressure vs. per cent oxygen, below which not even waxed paper or cotton terry cloth would ignite. A similar curve can probably be drawn for helium-oxygen mixtures and for helium-nitrogen-oxygen mixtures.

The value of such curves is that they give assurance to those who plan dives that if the percent oxygen is kept below a certain figure at a given pressure, the diver should be safe from all ordinary fire hazards. Fortunately, it appears that at pressures above atmospheric there is a region of gas composition and pressure in which fabrics do not burn, but in which human beings still get enough oxygen for breathing and respiration. We are not directly concerned under this contract with the physiologic limits, but we are very much interested in delineating the combustion limits. A start on this project was made during this past year, but more work must be done before a useful graph showing the region of non-combustion can be drawn.

It has been found that there is a borderline region between the conditions under which ignition of, e.g., paper, takes place with complete combustion and the conditions under which paper cannot be ignited at all. In our experiments we have found four sets of conditions for the ignition of strips of filter paper:

Ignitibility Code

1. The strip is ignited and burns completely.

2. The strip is ignited and burns for a length greater than one cm from the igniter, but the flame extinguishes itself before the strip is entirely consumed.

3. The strip is ignited to produce either a flame or smoldering, but there is no combustion past 1 cm from the igniter.

4. The strip is not ignited at all by the glowing igniter wire.

Our results to date with 6 mm x 160 mm strips of filter paper are given in the following tables:

Table No.	Angle of Strip	Gas Mixture	Water Vapor Added
20	45°	Oxygen-nitrogen	Yes
21	45°	Oxygen-helium	Yes
22	Vertical	Oxygen-nitrogen	No
23	Vertical	Oxygen-helium	No

The existence of the borderline region (ignitibility code 2 and 3) is clearly seen in these tables. Since we found that burning rates in dry gas are higher than in water-saturated gas, everything else being equal, and that they are higher in the vertical position than at 45°, the conditions for Tables 22 and 23 are considered to be more severe than those for the runs made with the strips at an angle of 45°.

It is planned eventually to confirm our results on the region of non-combustion with strips of waxed paper and of cotton terry cloth, both of which are readily flammable.

A comparison of the results for helium *vs.* nitrogen as diluents shows that borderline combustion takes place at higher oxygen concentrations when helium is the diluent; the region of non-combustion is therefore somewhat greater. This is in contrast to our finding that, for most of the conditions under which combustion takes place easily, the burning rates (once combustion has started) are higher when helium is the diluent.

XIX. THEORETICAL CONSIDERATIONS

During the past year, the work under this contract has been almost entirely empirical.

Huggett and his associates, in their first report [31], gave a general discussion of combustion theory. In their second report [30], they presented two items of theoretical interest: (1) They obtained a linear correlation between burn rate in various gas mixtures and the heat capacity of the mixture per mole of oxygen in the mixtures, and (2) they derived a simplified mathematical model (equation) to represent the burning process. This equation cannot, however, be used either for predicting absolute combustion rates or the effect of variation in gas composition on combustion rates, partly because of "difficulties in assigning realistic values to the various parameters."

In spite of the fact that Huggett obtained a linear correlation between the heat capacity of the gas mixture and the burning rate, he states [30, p. 13] that the much larger flame spread rate in helium-oxygen atmospheres as compared with nitrogen-oxygen atmospheres is attributable primarily to the higher thermal conductivities and, presumably, also higher diffusivities of the helium mixtures, and only secondarily to the higher flame temperatures associated with the lower heat capacity of helium. This statement seems to illustrate the fact that the theory is not yet well in hand.

Williams [58] had previously derived a simplified mathematical model for the burning of solids, but his equation is quite complicated.

Although solids can glow or smolder without producing a flame, the combustion of a solid is usually accompanied by a flame. If there is a flame, it is not actually the solid that is burning in the flame, but the evaporation or pyrolysis products of the solid.

The rate of burning of a solid by means of a flame depends chiefly on the following:

(1) the temperature available (from the igniter, from burning material, and from radiant heat reflected from the interior walls of the vessel),

(2) the pyrolysis temperature dependency of the solid,

(3) the nature of the pyrolysis products, and

(4) the composition and pressure of the ambient gas.

The most important factors that limit the combustion rate appear to be:

(a) the rate of pyrolysis of the solid,

(b) the rate with which heat can be brought to the unburned sample (by conduction, radiation, etc.).

(c) the rates of diffusion and convection which bring fuel molecules into contact with oxygen molecules through molecules of inert gases or combustion products, and

(d) the rate of loss of heat from the reaction zone by radiation.

Which of the four factors is the limiting one depends on the conditions. For example (a), the rate of pyrolysis, is probably the limiting factor at lower temperatures. Another example: at zero gravity, either (a) or (c) is usually the limiting factor.

All our curves for rate of combustion vs. total pressure tend to flatten out as the pressure becomes higher, because in every case one or more of the four rate-limiting factors tend to slow down the combustion. It is conceivable that at sufficiently high pressures, the rate could even start to decrease because of the decreasing rate of diffusion of gas molecules (c).

XX. GENERAL INFORMATION

A. Diving Pressure Equivalents

Table 24 gives equivalent values for pressures in fsw, atm. abs., and psia. This table also gives the partial pressure of oxygen in air at pressures from 0 to 300 fsw.

Use of air alone is of little or no interest at pressures greater than 300 fsw. Table 25 gives the pressure equivalents from 310 to 1540 fsw, but not the partial pressures of oxygen in air at these pressures.

B. List of Materials Found in Diving Chambers

Two lists of materials were furnished to us, one (Table 26) by the U.S. Navy Experimental Diving Unit, the other (Table 27) by the Linde Bioresearch Group and Ocean Systems, Inc.

C. Conditions for Various Partial Pressures of Oxygen

For reasons of both physiology and safety, questions frequently arise as to the conditions (total pressure and mole-%) under which the partial pressure of oxygen has a

given value. These conditions are given for 0.21, 0.5, 1, 1.5, 2, 2.5, and 3 atm of oxygen in Figures 29 and 31.

D. Registered Trademarks and Organization Addresses

Listed below are some of the registered trademarks used in this article, together with their owners. This list is given here to help the companies protect their trademarks and to remove the necessity of enclosing them in quotation marks each time they occur. Names of the various organizations that supplied samples or were otherwise connected with this project are given in alphabetical order, together with their addresses when known.

Organization	Trade Name
Armour Industrial Chemical Company	Ethoquad
American Brattice Cloth Corporation Warsaw, Indiana 45680 Attn: Mr. D. B. Mikesell	-
Dow Badische Company 350 Fifth Avenue New York, N. Y. 10001 Attn: Mr. H. Z. Heuston	Rovana
Dow Chemical Company Technical Service & Development 2020 Abbott Road Center Midland, Michigan 48640 Attn: Mr. E. D. Aman	-
Dow Corning Corporation Fabricating Materials Department Midland, Michigan 48640 Attn: Mr. D. K. Closs	Silastic
E. I. du Pont de Nemours & Company Elastomers Chemicals Department Wilmington, Delaware 19898	Hypalon, Viton
E. I. du Pont de Nemours & Company Film Department Wilmington, Delaware 19898 Attn: Mr. D. F. Fiala	Kapton, Mylar
E. I. du Pont de Nemours & Company Industrial Fabrics Section WT902 Wilmington, Delaware 19898	Armalon, Fairprene

Organization	Trade Name
E. I. du Pont de Nemours & Company Textile Fibers Department Centre Road Building Wilmington, Delaware 19898 Attn: Mr. Wallace P. Behnke Mr. Joseph R. Ruddy Mr. Benjamin T. Sharp	Nomex, Teflon
M. J. Fassler Corporation	Fasslon
FMC Corporation P.O. Box 8 Princeton, New Jersey 08540 Attn: Mr. Paul E. Willard	Avceram
General Electric Company Silicone Products Department Waterford, New York 12188 Attn: Mr. T. C. Taylor	-
Hooker Chemical Corporation P.O. Box 344 Niagara Falls, New York 14302 Attn: Mr. Frank Grano	Roxel
International Telephone & Telegraph Corporation Wire and Cable Division Department E Clinton, Massachusetts 01510	-
Mine Safety Appliances 201 North Braddock Avenue Pittsburgh, Pennsylvania 15208 Attn: Mr. G. L. Morse	-
Office of Naval Research Constitution Avenue at 18th Street Washington, D. C. 20360 Attn: Lt. Cmdr. T. W. Robinson	
Owens-Corning Fiberglas Corporation Yarn & Fabric Finishing Development Laboratory Ashton, Rhode Island 02864 Attn: Mr. J. J. Dillon	Beta Fiberglas
Reaction Motors Division of Thiokol Denville, New Jersey 07834 Attn: Mr. Saul Frank	-

Organization	Trade Name
Reinforced Air Corporation Old Lyme, Connecticut 06371 Attn: Mr. John B. McPherson	Isoschaum
Schlosser Textile Company, Inc. 76 Madison Avenue New York, N. Y. 10016	-
Stern and Stern Textiles, Inc. Huguet Fabrics Division Hornell, New York 14843 Attn: Mr. John W. Dupont	-
J. P. Stevens & Co., Inc. 1460 Broadway New York, N. Y. 10036 Attn: Mr. Paul Motzenbecker	Wonder Shield
Union Carbide Corporation Fibers and Fabrics Division 270 Park Avenue New York, N. Y. 10017	Dynel
Uniroyal Fiber & Textile Division Uniroyal Inc. Hogansville, Georgia 30230 Attn: Mr. D. T. Austin Dr. G. C. Holroyd	Asbeston
Uniroyal Fiber & Textile Division Uniroyal Inc. 1230 Avenue of the Americas New York, N. Y. 10020 Attn: Mr. Walter C. Hitchcock	Asbeston
Uniroyal Fiber & Textile Division Uniroyal, Inc. 350 Columbia Road Winnsboro, South Carolina 29180 Attn: Mr. Edward A. Morris	Asbeston
U.S. Navy Experimental Diving Unit Building 214 Washington Navy Yard Washington, D. C. 20390 Attn: Lt. Cmdr. John V. Harter	-
Wheeler Protective Apparel, Inc. 224 West Huron Street Chicago, Illinois 60610 Attn: Mr. H. L. Wheeler	-

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TABLE 1

TENTATIVE CLASSIFICATION OF TESTED CLOTH FABRICS

Class 0

Cotton and cotton terry cloth

J.P. Stevens

Wonder Shield coated with "Fasslon G"

Uniroyal

Orlon, Style 20543 F

Class 1

Wool

Class 2

Hooker Chemical

Roxel (cotton treated with THPC)

Class 3

American Brattice Cloth

Brattice cloth, yellow plastic reinforced with nylon fabric, Grade 12NP

Brattice cloth, yellow polyvinylchloride sheeting, Grade 20Y

Dow Chemical

APO-treated cotton sateen

Hooker Chemical

Cloth woven of 50% Nomex and 50% cotton fibers, treated with THPC (referred to as 50:50 Nomex-Roxel)

TABLE 1 (continued)

Wheeler Protective Apparel

Cotton, green, No. 60

Unknown manufacturer

Submarine flameproofed mattress cover coated with rubber, supplied by U.S. Navy Experimental Diving Unit

Class 4

DuPont

Nomex, butyl-coated, Fairprene 88-003

Hooker Chemical

Wool treated with THPC

Mine Safety Appliances

Fire-retardant wool blanket, No. 04-12487

Class 5

Dow Badische

Rovana, Patterns 5700 and 6400
Pattern 5800 coated on one side with PVC

J.P. Stevens

Wonder Shield - plain (coated Beta Fiberglas). Only the thin coatings burn.

Uniroyal

Asbeston Style S/5670-FEL coated on one side with aluminum

Asbeston (experimental) basic style S/6555, but coated with either one coat (F-3339-A) or two coats (F-3339-B) of pink PVC

TABLE 1 (continued)

Dynel, Styles 907 and 907F (fiber manufactured by Union Carbide)

Wheeler Protective Apparel

Cotton, khaki, No. 61

Asbestos, Underwriters' Grade Basket Weave

Class 6

American Brattice Cloth

Brattice cloth, Navy

Dow Corning

Glass cloth coated with Silastic S-2316U*

DuPont

Nomex cloth

Nomex cloth, terry knit (so far tested only for Class 5, but probably belongs here in Class 6)

Teflon-coated Nomex cloth, Armalon 98-101

Uniroyal

Dynel tent material (no number given)

Asbestos woven with Dynel, Asbeston Style S/1445

Asbestos cloth, lightly coated, Asbeston Style S/3620-IAR

Wheeler Protective Apparel

Fiberglas cloth coated with pigmented ("silvrprened") neoprene

- -

*Our tests on this material have not yet been completed. It may be in a higher class.

TABLE 1 (concluded)

Class 8

DuPont

Teflon TFE, brown and white cloth

Teflon-coated fiber glass cloth, "Armalon, TFE-Fluorocarbon Resin Coated Glass Fabric." No number given.

FMC Corporation

Avceram CS

Class 9 (non-flammable)

Owens-Corning

Beta Fiberglas

Uniroyal

Type D67054, experimental samples of asbestos cloth

TABLE 2

TENTATIVE CLASSIFICATION OF ELASTOMERS AND FLEXIBLE TUBING

Class 0 (readily flammable)

Natural, synthetic, or ordinary silicone rubber

Class 2

Dow Corning Silastic S-2316U

General Electric SE-9029 and SE-9044

Class 3

DuPont Hypalon

Class 6

DuPont Viton

Class 8

DuPont Teflon as flexible corrugated tubing*

Stainless steel flexible corrugated hose**

Table 9 (nonflammable)

Thiokol carboxy nitroso rubber terpolymer

---

*Not tested by us in this form

**Not tested by us

TABLE 3

TENTATIVE CLASSIFICATION OF PAINT AND OTHER FILM MATERIAL, INSULATION, AND PILLOW STUFFING

Class 0 (readily flammable)

Paint: Heat-resistant aluminum primer, Federal Stock No. 8010-815-2692.

Class 1

White cover paint (enamel), Military Specification Mil. E-17970L, September 19, 1961, non-flaming (dry) chlorinated alkyd resin, soft-white, semigloss, Formula No. 12458, Federal Stock No. 8010-577-4738.

Class 2

Dow Corning Silastic S-2316U (can be applied as a latex film).

Union Carbide, experimental urethane foam No. 584 RD 69.

Class 5

DuPont Kapton film, Type 100H

DuPont Nomex and Havolite batting*

Class 7

DuPont Kapton film, Types 300H and 200 F 919

Class 8

ITT Type WTE electric wire insulation

Class 9 (non-flammable)

DuPont Kapton electric wire insulation, Type 019-919

- -

*Our tests on these materials have not yet been completed

TABLE 4

COMBUSTION RESULTS PUBLISHED BY THE RAF INSTITUTE OF AVIATION MEDICINE, ENGLAND

Gas Pressure, atm.	Denim Ignition time, sec. Squares	Denim Ignition time, sec. Sleeves	Area Burned, cm^2 Denim Squares in 10 sec.	Area Burned, cm^2 Denim Sleeves in 15 sec.	Area Burned, cm^2 Pig skin in 15 sec.	Comment
1 Air	-	-	0	0	0	No ignition
2 Air	6.5	5.0	19	46	30	No flash
3 Air	4.5	4.5	26	34	65	No flash
4 Air	4.5	3.5	34	150	332	No flash
5 Air	3.5	1.5	44	169	158	No flash
1 O_2	<0.5	<0.5	225	1300	1500	Flash fire

Table 4

TABLE 5

IGNITION TEMPERATURE OF FILTER PAPER STRIPS IN COMPRESSED AIR AT VARIOUS ANGLES

Total Air Pressure		Partial Pressure	Ignition Temperature, °F					
fsw	atm.	of O_2, atm.	Horizontal	22.5°	45°	60°	75°	Vertical
0	1	0.21	830 850	775	750 800 805	820	930	815 925
50	2.51	0.53	-	770	750	740	750 835	765 800
100	4.03	0.84	770	680	685 710	745	800 810	735
200	7.06	1.48	740	700	600 670	690 700	670 750	665
300	10.08	2.11	710	640	600 690	640	640 700	635

TABLE 6

IGNITION TEMPERATURE OF FILTER PAPER STRIPS AT 45° ANGLE AS A FUNCTION OF GAS COMPOSITION AND PRESSURE

Total pressure, atm. abs. / fsw			Ignition Temperature, °F			
			1.00 0	4.03 100	7.06 200	10.09 300
%O_2	%N_2 (a)	%He				
50.3	49.7	0.0	800 820,820	665	635	620
30.9	69.1	0.0	840,780,800,815	685	560 600 720	660
20.95,b	79.05	0.0	810,830,840 785	710	670	690
49.5	0.0	50.5	825	690	625	-
30.3	0.0	69.7	890,c	710	705	660
20.3	0.0	79.7	1130,d	730	690	660

(a) Includes any argon that was present.

(b) Compressed air.

(c) This temperature is higher than the corresponding temperatures measured when the diluent was nitrogen.

(d) In two other cases, no ignition took place, even though the temperature of the igniter reached 1470°F.

TABLE 7

IGNITION DELAY FOR PAPER STRIPS AT A 45° ANGLE IN NITROGEN-OXYGEN AND IN HELIUM-OXYGEN MIXTURES

Total Pressure		Ignition Delay, sec.	
fsw	atm. abs.	79% N_2 + 21% O_2 (a)	79.7% He + 20.3% O_2
0	1.00	2.66	b
50	2.51	2.81	3.20
100	4.03	2.66	3.05
200	7.06	2.51	3.45
300	10.09	3.05	4.18

Condition: Constant current of 5 amperes through igniter wire.

(a) Air

(b) No ignition after over 40 sec. at 1470°F.

TABLE 8

EXPERIMENTAL RATES OF COMBUSTION OF PAPER STRIPS IN SIMULATED COMPRESSED AIR AT VARIOUS ANGLES

Pressure, ft. of sea water	Combustion Rate, cm/sec				
	Horizontal	22.5°	*45°	60°	75°
0	0.36	0.63	1.12	1.71	2.92
50	**0.41	0.87	1.48	2.22	3.42
100	0.46	1.06	1.78	**3.15	**4.20
200	0.48	1.24	2.39	3.38	4.00
300	0.48	1.35	2.92	4.20	4.64

*From curve in Figure 19.

**From curve in Figure 20.

TABLE 9

TYPICAL MEASURED BURNING RATES FOR STRIPS OF FILTER PAPER AT 45° ANGLE

Total pressure, atm. abs.			Burn Rate, cm/sec					
		fsw	0.21 -	0.53 -	1.00 0	4.03 100	7.06 200	10.09 300
Gas Composition (dry basis)								
%O_2	%N_2 (a)	%He						
99.6	0.4	0.0	2.32	3.13	4.19	d	d	d
50.3	49.7	0.0	1.13 1.17	1.44	2.36	3.72 3.77	5.10 4.06	6.34
20.95,b	79.05	0.0	c	0.80	1.17 1.17 1.10	1.82 1.78	2.80 2.28	3.13 3.25
49.5	0.0	50.5	1.24	1.87 1.90	2.96 2.89 2.89	4.06	4.90 4.82	d
20.3	0.0	79.7	c	c	c	2.23	2.61	2.49
47.0	24.6	28.4	d	d	2.74 2.68	3.66	4.41 4.64	5.53 6.78
20.9	39.6	39.5	d	d	1.38 1.38 1.35 1.27	2.28 2.28 1.97 2.28 1.81 1.72	2.71 2.83 2.74	3.72 3.13 3.56 3.33 3.47

(a) Includes any argon that was present.

(b) Compressed air.

(c) Sample would not burn, even with brightly glowing igniter grid.

(d) No run was made under these conditions.

TABLE 10

ADDITIONAL GAS MIXTURES IN WHICH BURNING RATES WERE MEASURED

Binary Mixtures, Mole-%			Ternary Mixtures, Mole-%		
O_2	N_2	He	O_2	N_2	He
41.3	58.7	0	-	-	-
30.9	69.1	0	29.3	11.1	59.6
24.9	75.1	0	25.4	10.6	64.0
22.5	77.5	0	20.3	10.8	68.9
18.0	82.0	0	18.0	10.6	71.4
15.3	84.7	0	15.3	11.0	73.7
39.9	0	60.1	43.0	28.0	29.0
30.3	0	69.7	30.6	35.5	33.9
25.2	0	74.8	25.7	36.4	37.9
15.6	0	84.4	15.3	42.4	42.3

Note: The experimental results from all the gas mixtures listed above were used, along with the results given in Table 9, in deriving Equations 1 and 2 to correlate the data.

TABLE 11

FIT OF EMPIRICAL EQUATIONS TO EXPERIMENTAL DATA

Deviation of Calculated from Experimental Rate	Number of Experimental Points	
	Equation 1	Equation 2
0 to 10%	73	98
10 to 20%	39	66
20 to 30%	17	32
30 to 40%	4	13
over 40%	3	0
Total	136	209

Note: Equation 1 is for gas mixtures containing 21% or less oxygen by volume, and for over 99% oxygen. Equation 2 is for the range 22% to 50% oxygen.

TABLE 12

DIRECT COMPARISON OF BROWN AND WHITE TEFLON CLOTH

Gas	Total Pressure fsw	Total Pressure psia	Angle of Sample	Burn Rate, cm/sec White	Burn Rate, cm/sec Brown
100% O_2	-	5.0	45°	a	a
	-	10.0	45°	0.25	0.39
	-	14.7	45°	0.39	0.68
	-	14.7	Vertical	0.95	1.7
50% O_2 + 50% N_2	-	14.7	45°	a	a
	100	59	45°	0.216	0.224
50% O_2 + 50% He	100	59	45°	a	a
	200	104	45°	0.40,0.57	0.27,b

(a) Burned in contact with igniter, but self-extinguishing within 2 cm of igniter.

(b) Extinguished itself 6.7 cm from the igniter.

Notes: Samples supplied by Stern and Stern, brown = T3-42; white = T160-42. The tests were alternated between brown and white so as to get as direct a comparison as possible.

TABLE 13

SEPARATE TESTS ON BROWN TEFLON CLOTH

Total Pressure		Burning Rate, cm/sec		
		41.3% O_2 + 58.7% N_2	99.6% O_2	
fsw	psia	Vertical	45°	Vertical
-	3.08	-	a	a
-	7.8	-	a	b
-	12.3	-	0.73	2.60,c
0	14.7	d	-	-
-	17.0	-	1.42	-
-	21.8	-	0.63	3.02,c
-	31.2	-	1.23	3.47
100	59.2	0.63	-	-
200	104	1.27	-	-
300	148	2.55	-	-

(a) Burned only at or near the igniter, then extinguished itself.

(b) Smoldered for 5 cm after the igniter, then extinguished itself.

(c) In another run the strip smoldered and curled for its entire length, but there was no flame.

(d) Flame extinguished itself before reaching the last thermocouple.

Notes: This cloth was Stern and Stern pattern T3-42. Brown Teflon was self-extinguishing in 30% O_2 - 70% N_2. In 25% O_2 - 75% N_2, Teflon gave a small blue flame in contact with the igniter, but there was no combustion beyond that point. For further tests on brown Teflon cloth, see Table 12.

TABLE 14

GLASS CLOTH COATED WITH TEFLON

	Burn Rate, cm/sec		
	0	100	200 fsw
30.9% O_2 + 69.1% N_2	-	0.76	0.86
41.3% O_2 + 58.7% N_2	Self-extinguishing	0.83	1.15
50.3% O_2 + 49.7% N_2	0.46	1.55	1.73

Note: Tests made on samples 12 x 160 mm held in the vertical position. Sample was identified only as a DuPont "Armalon," (no number). The glass cloth base was woven from silicone-lubricated glass fiber.

TABLE 15

IGNITION TEMPERATURES FOR CLOTH STRIPS HELD IN THE VERTICAL POSITION IN COMPRESSED AIR

Pressure, ft. of Sea Water	Partial Pressure of O_2, atm.	Cotton Broadcloth	Roxel-treated Broadcloth	Wool	Nomex	TFE Teflon
0	0.21	950 980	840 980	1000 1010 1050	955 1080 1125	-
25	0.37	-	-	-	1005	-
50	0.53	-	-	-	890	-
100	0.84	710 800	710	930	920 930 980	1195 1220*
150	1.16	-	-	-	970 980 1055	-
200	1.48	680	700 705	910	980 1090	-
250	1.80	-	-	-	1050	-
300	2.11	680	635 665	965	895 990 1000	1115

The ignition temperatures are in °F.

The fact that an ignition temperature is given in this table does not mean that the fabric continued to burn after ignition.

*After the first flame went out, a second was temporarily produced by raising the temperature to 1220°F on the same sample. In all other cases in this table, different temperatures mean different samples.

TABLE 16

BURNING RATE OF CLOTH STRIPS HELD AT AN ANGLE OF 45° IN COMPRESSED AIR

Total Pressure		Burning Rate, cm/sec				
fsw	psia	Cotton Terry Cloth	Cotton Broadcloth	Roxel Cotton Broadcloth	Wool	Nomex
0	14.7	0.58 0.71	1.16 1.76	c,e,e	c,c	d,d
50	37	1.65	2.41	-	-	d
100	59	3.56	7.88	c	0.71	0.22,d
200	104	5.78,b	11.82,b	c	0.70 0.74	d
250	126	-	-	c	-	-
300	148	8.97,b	a,b,b	6.84,c,c,c	c	d

(a) Rate was too fast to measure.

(b) In another test, rate was also too fast to measure.

(c) Sample ignited with a strong flame which extinguished itself before reaching the last thermocouple.

(d) Same as (c), except flame was weak.

(e) Sample did not ignite, even in contact with the igni .

Repeated footnote letters signify repeated experiments.

TABLE 17

BURNING RATE FOR VERTICAL CLOTH STRIPS IN COMPRESSED AIR

Total Pressure		Burning Rate, cm/sec			
		Roxel Cotton			
fsw	psia	Broadcloth	"Worklon"	Wool	Nomex
0	14.7	a	a	2.08,d	a
15	21.5	-	c	-	-
25	26	-	d	-	0.52
50	37	b	d	-	0.85
75	48	b	-	-	-
100	59	b	b	2.52	0.77,d
-	70	c	-	-	-
-	81	c	-	-	a
200	104	c,d	c	2.17	0.66,d
-	126	c	-	-	0.91
-	148	2.92, 3.10, 3.21, c,d	-	1.04	b

Cotton terry cloth and cotton broadcloth burned too rapidly to make rate measurements.

Teflon cloth ignited (to give a small blue flame) in contact with the igniter at pressures of 59 psia (100 fsw) and above, but was self-extinguishing beyond the igniter.

Beta Fiberglas fabric neither ignited nor burned.

(a) Fabric ignited, but flame extinguished itself just beyond the igniter.

(b) Fabric ignited, but extinguished itself before reaching the upper end of the sample strip.

(c) The flame climbed up part way, and then the strip smoldered part or all of the rest of the way.

(d) The flame climed all the way to the top; no clear thermocouple peaks were seen on the recorder chart due to the height of the initial flame.

TABLE 18

BURNING RATES FOR VERTICAL CLOTH STRIPS AT 25% AND HIGHER OXYGEN PERCENTAGES

Total Pressure	Roxel Cotton Broadcloth,	Burning Rate, cm/sec			
		Nomex		Teflon	
psia	24.9% O_2	24.9% O_2	30.9% O_2	30.97% O_2	41.3% O_2
14.7	a	1.13	b	c	c
26	-	-	b	-	-
37	6.43	1.54	1.19	-	-
59	6.67	1.33 1.61 2.06	2.48	c	0.63
104	a	1.00 1.36	b	c	1.27
148	a	1.97	b	c	2.55

The diluent in all cases was nitrogen.

In 24.9% O_2, woll and untreated cotton broadcloth burned so rapidly that the rate could not be measured.

In 24.9% O_2, Teflon gave a small blue flame in contact with the igniter, but there was no combustion beyond the igniter.

Beta Fiberglas did not burn at all.

(a) Sample burned so rapidly that the rate could not be measured.

(b) Although the rate of combustion of the main part of the strip was low, the initial flame was so high that the second thermocouple was heated at the same time as the first; hence, no rate could be measured.

(c) Flame extinguished itself before reaching the last thermocouple.

TABLE 19

NOMEX TERRY-KNIT CLOTH

	Observations and Burn Rate		
	0	100	200 fsw
Compressed air, 45° angle	Self-ex. near igniter	Self-ex. near igniter	Self-ex. near igniter
Compressed air, vertical sample	Self-ex. 1.5 cm from igniter	Self-ex. 3.5 cm from igniter	Self-ex. 2 cm from igniter
25.2% O_2 + 74.8% N_2, vertical	Ignited at 1100°F. and burned slowly all the way	Ignited at 895°F. Burned slowly all the way	Ignited at 880°F. Burned and smoldered all the way

Note: In no case did the nap on the Terry-knit Nomex flare up. Time did not permit testing at higher oxygen percentages.

TABLE 20

EXPLORATION OF REGION OF NONCOMBUSTION

Filter paper strips at 45° in oxygen-nitrogen mixtures

Mole-% Oxygen	Ignitibility Code										
	0	25	50	100	150	200	250	300	600	800	1000 fsw
18.0	1	1	1	1	1	1	1	1	1	1	1
15.3	2	1	1	1	1	1		1	1	1	1
12.3	2-3				2-3			2-3	2-3	2-3	2-3
10.4	3	2-3	3	3	3			3			3
4.8	4										4

Notes: Gas mixture was saturated with water vapor. For ignitibility code, see text, Section XVIII. Note that under some conditions the results obtained with two or mor[illegible]mples fell in a range of combustibility rather than in a single category.

Table 20

TABLE 21

EXPLORATION OF REGION OF NONCOMBUSTION

Filter paper strips at 45° in oxygen-helium mixtures

Mole-% Oxygen	Ignitibility Code											
	0	25	50	100	150	200	250	300	400	600	800	1000 fsw
25	1	1	1	1	1	1	1	1	1	1	1	1
20.3	1-4	1	1	1	1	1	1	1	1	1	1	1
15.6	3-4	-	2	1	1-2	1	1-2	1	1	1	1	1
10.1	3-4	-	3	3	3	2-4	4	3-4	-	2-3	-	2-3

Notes: Gas mixture was saturated with water vapor. For ignitibility code, see text, Section XVIII. Note that under some conditions the results obtained with two or more samples fell in a range of combustibility rather than in a single category.

TABLE 22

EXPLORATION OF REGION OF NONCOMBUSTION

Vertical strips of filter paper in oxygen-nitrogen mixtures

Mole-% Oxygen	Ignitibility Code									
	0	25	50	75	100	150	200	300	640	fsw
20.95	1		1		1		1	1		
15.3	2	1	1							
12.3	2				2			2-3	2	
10.4	3	3	3	3	3	3		3		
4.8	4				4			4		

Notes: No water vapor was added to the gas mixtures before the ignition tests. For ignitibility code, see test, Section XVIII. Note that under some conditions the results obtained with two or more samples fell in a range of combustibility rather than in a single category.

TABLE 23

VERTICAL STRIPS OF FILTER PAPER IN OXYGEN-HELIUM MIXTURES

Mole-% Oxygen	Ignitibility Code									
	0	15	25	50	75	100	125	300	785	fsw
20.3	3	1	1	1		1				
15.6	3				3	1-3				
10.1	3							4	4	

Notes: No water vapor was added to the gas mixture before the ignition tests. For ignitibility code, see text, Section XVIII. Note that under some conditions the results obtained with two or more samples fell in a range of combustibility rather than in a single category.

TABLE 24

DIVING PRESSURE EQUIVALENTS, 0 to 300 FSW

Depth, fsw	Total Pressure		Partial Pressure of Oxygen in Air	
	atm. abs.	psia	atm.	psi
0	1.00	14.70	0.21	3.08
10	1.30	19.15	0.27	4.01
20	1.61	23.60	0.34	4.94
25	1.76	25.82	0.37	5.41
30	1.91	28.05	0.40	5.88
40	2.21	32.50	0.46	6.81
50	2.51	36.95	0.53	7.74
60	2.82	41.40	0.59	8.67
70	3.12	45.85	0.65	9.60
75	3.27	48.07	0.69	10.07
80	3.42	50.30	0.72	10.54
90	3.73	54.75	0.78	11.47
100	4.03	59.20	0.84	12.40
110	4.33	63.65	0.91	13.33
120	4.63	68.10	0.97	14.27
125	4.79	70.32	1.00	14.73
130	4.94	72.55	1.03	15.20
140	5.24	77.00	1.10	16.13
150	5.54	81.45	1.16	17.06
160	5.84	85.90	1.22	18.00
170	6.15	90.35	1.29	18.93
175	6.30	92.57	1.32	19.39
180	6.45	94.80	1.35	19.86
190	6.75	99.25	1.41	20.79
200	7.06	103.70	1.48	21.72
210	7.36	108.15	1.54	22.66
220	7.66	112.60	1.61	23.59
225	7.81	114.82	1.64	24.05
230	7.96	117.05	1.67	24.52
240	8.27	121.50	1.73	25.45
250	8.57	125.95	1.80	26.39
260	8.87	130.40	1.86	27.32
270	9.18	134.85	1.92	28.25
275	9.33	137.07	1.95	28.72
280	9.48	139.30	1.99	29.18
290	9.78	143.75	2.05	30.11
300	10.08	148.20	2.11	31.05

TABLE 25

DIVING PRESSURE EQUIVALENTS, 310 to 1540 FSW

Depth, fsw	Total Pressure atm. abs.	psia	Depth, fsw	Total Pressure atm. abs.	psia
310	10.39	152.65	640	20.38	299.50
320	10.69	157.10	650	20.68	303.95
325	10.84	159.32	660	20.99	308.40
330	10.99	161.55	670	21.29	312.85
340	11.30	166.00	675	21.44	315.07
350	11.60	170.45	680	21.59	317.30
360	11.90	174.90	690	21.89	321.75
370	12.20	179.35	700	22.20	326.20
375	12.36	181.57	710	22.50	330.65
380	12.51	183.80	720	22.80	335.10
390	12.81	188.25	725	22.95	337.32
400	13.11	192.70	730	23.10	339.55
410	13.41	197.15	740	23.41	344.00
420	13.72	201.60	750	23.71	348.45
425	13.87	203.82	760	24.01	352.90
430	14.02	206.05	770	24.32	357.35
440	14.32	210.50	775	24.47	359.57
450	14.63	214.95	780	24.62	361.80
460	14.93	219.40	790	24.92	366.25
470	15.23	223.85	800	25.22	370.70
475	15.38	226.07	810	25.53	375.15
480	15.53	228.30	820	25.83	379.60
490	15.84	232.75	825	25.98	381.82
500	16.14	237.20	830	26.13	384.05
510	16.44	241.65	840	26.44	388.50
520	16.75	246.10	850	26.74	392.95
525	16.90	248.32	860	27.04	397.40
530	17.05	250.55	870	27.34	401.85
540	17.35	255.00	875	27.50	404.07
550	17.65	259.45	880	27.65	406.30
560	17.96	263.90	890	27.95	410.75
570	18.26	268.35	900	28.25	415.20
575	18.41	270.57	910	28.56	419.65
580	18.56	272.80	920	28.86	424.10
590	18.87	277.25	925	29.01	426.32
600	19.17	281.70	930	29.16	428.55
610	19.47	286.15	940	29.46	433.00
620	19.77	290.60	950	29.77	437.45
625	19.93	292.82	960	30.07	441.90
630	20.08	295.05	970	30.37	446.35

TABLE 25 (continued)

Depth, fsw	Total Pressure atm. abs.	Total Pressure psia
975	30.52	448.57
980	30.67	450.80
990	30.98	455.25
1000	31.28	459.70
1010	31.58	464.15
1020	31.89	468.60
1025	32.04	470.82
1030	32.19	473.05
1040	32.49	477.50
1050	32.79	481.95
1060	33.10	486.40
1070	33.40	490.85
1075	33.55	493.07
1080	33.70	495.30
1090	34.01	499.75
1100	34.31	504.20
1110	34.61	508.65
1120	34.91	513.10
1125	35.07	515.32
1130	35.22	517.55
1140	35.52	522.00
1150	35.82	526.45
1160	36.13	530.90
1170	36.43	535.35
1175	36.58	537.57
1180	36.73	539.80
1190	37.03	544.25
1200	37.34	548.70
1210	37.64	553.15
1220	37.94	557.60
1225	38.09	559.82
1230	38.24	562.05
1240	38.55	566.50
1250	38.85	570.95
1260	39.15	575.40
1270	39.46	579.85
1275	39.61	582.07
1280	39.76	584.30
1290	40.06	588.75
1300	40.36	593.20
1310	40.67	597.65
1320	40.97	602.10
1325	41.12	604.32
1330	41.27	606.55
1340	41.58	611.00
1350	41.88	615.45
1360	42.18	619.90
1370	42.48	624.35
1375	42.64	626.57
1380	42.79	628.80
1390	43.09	633.25
1400	43.39	637.70
1410	43.70	642.15
1420	44.00	646.60
1425	44.15	648.82
1430	44.30	651.05
1440	44.60	655.50
1450	44.91	659.95
1460	45.21	664.40
1470	45.51	668.85
1475	45.66	671.07
1480	45.81	673.30
1490	46.12	677.75
1500	46.42	682.20
1510	46.72	686.65
1520	47.03	691.10
1525	47.18	693.32
1530	47.33	695.55
1540	47.63	700.00

Table 25
(concluded)

TABLE 26

MATERIALS IN DIVING CHAMBERS AS LISTED BY THE U.S. NAVY EXPERIMENTAL DIVING UNIT

Air conditioning system
Bags, polyethylene
Bara lime
Belts, weight
Blankets

Books and magazines
Buckets
Bunk, canvas bottom
Camera, T.V.
Cards

Chain, brass
Communications System
Cotton line
Electrical fitting (med.)
Fins

Fire Extinguisher, carbon-dioxide type
Food
Gage, caisson
Gage, humidity
Hammer, rawhide

Hose, H.P. rubber
Inhalators
Lighting, emergency
Lighting System
Mattress

Mattress cover, fire retardant
Masks, face
Medical gear
Paint, white, fire retardant
Pants, sweat

Paper
Paper, toilet
Pencils
Pillows
Purafil

Robes, nylon
Robes, terrycloth
Sand
Scrubber, carbon dioxide
Sheets

Shirts, sweat
Shoes, rubber, shower
Shoes, tennis
Soda lime
Swimming trunks

Telephone, sound power
Thermometer
Towels
Tubing, plastic
Underwear, diving

Winch, air
Wood
Wrench, dogging
Wrench, medical lock
Wrench, wing nut

TABLE 27

MATERIALS IN DIVING CHAMBERS AS LISTED BY THE LINDE BIORESEARCH GROUP AND OCEAN SYSTEMS, INC.

ELASTOMERS	Boots, shoes, and swim fins
	Bumpers and pads, various types of dense rubber
	Gaskets around doors, etc.
	Hoses, high pressure
	"O" rings
	Oxygen masks and hoses (with or without cotton stockinette covering)
	Sponge and foam rubber padding
	Underwater face masks
	"Wet" suits (1/4-inch thick neoprene foam)
	Wiring insulation
MISCELLANEOUS	Human skin and hair
	Plywood
	Telephone handset
	Wool
PAINT	*Aluminum paint on rusted iron
	Enamel paint
	Fire-retardant paint

*Question: Does this present a thermite problem?

TABLE 27 (continued)

PAPER	Books	
	Kleenex	
	Loose paper, note pads, etc.	
	Magazines and newspapers	
PLASTICS, vinyl (PVC)	Hoses, breathing gas	
	Plastic sheets or film	
	Thermal underwear (being developed)	
	Tubing of various sizes and uses	
	Wiring insulation	
PLASTICS, other	Polyethylene bottles	
	Polyethylene film (bags, etc.)	
	Polyethylene wiring insulation	
	Teflon tubing	
	Teflon wiring insulation	
	Nylon, Plexiglas, Polycarbonate, Polypropylene	usually will be small items
TEXTILES, Cotton Cloth	Bedding - blankets, hammocks, mattress covers, quilts, sheets	
	Clothing - canvas, hard drill, knitted fabrics, sneakers	
	Terrycloth - bathrobes, towels	

TABLE 27 (concluded)

TEXTILES, other	Blankets, wool
	Clothing, wool
	Clothing and other fabrics, nylon
	Fiberglas fabrics, with and without resin treatment
	Leather
	Leatherette (plastic coated cloth)
	Rope - hemp, cotton and nylon
	Synthetic fabrics (Dynel, Dacron, rayon, etc.)

TABLE 28

CONDITIONS FOR VARIOUS PARTIAL PRESSURES OF OXYGEN, 0 to 300 fsw

Desired Partial Pressure of O_2, atm. abs.	Mole-% Oxygen								
	0	25	50	100	150	200	250	300	fsw total pressure
	1.00	1.76	2.51	4.03	5.54	7.06	8.57	10.08	atm. abs.
0.21	21	11.9	8.37	5.21	3.79	2.97	2.45	2.08	
0.50	50	28.4	19.9	12.4	9.03	7.08	5.83	4.96	
1.00	100	56.8	39.8	24.8	18.1	14.2	11.7	9.92	
1.50	-	85.3	59.8	37.2	27.1	21.2	17.5	14.9	
2.00	-	-	79.7	49.6	36.1	28.3	23.3	19.8	
2.50	-	-	99.6	62.0	45.1	35.4	29.2	24.8	
3.00	-	-	-	74.4	54.2	42.5	35.0	29.8	

TABLE 29

CONDITIONS FOR VARIOUS PARTIAL PRESSURES OF OXYGEN, 400 to 1500 fsw

Desired Partial Pressure of O_2, atm. abs.	400 13.11	500 16.14	600 19.17	750 23.71	1000 31.28	1250 38.85	1500 46.42	fsw total pressure atm. abs.
0.21	1.60	1.30	1.10	0.89	0.67	0.54	0.45	
0.50	3.81	3.10	2.61	2.11	1.60	1.29	1.08	
1.00	7.63	6.20	5.22	4.22	3.20	2.57	2.15	
1.50	11.4	9.29	7.82	6.33	4.80	3.86	3.23	
2.00	15.3	12.4	10.4	8.44	6.39	5.15	4.31	
2.50	19.1	15.5	13.0	10.5	7.99	6.44	5.39	
3.00	22.9	18.6	15.6	12.7	9.59	7.72	6.46	

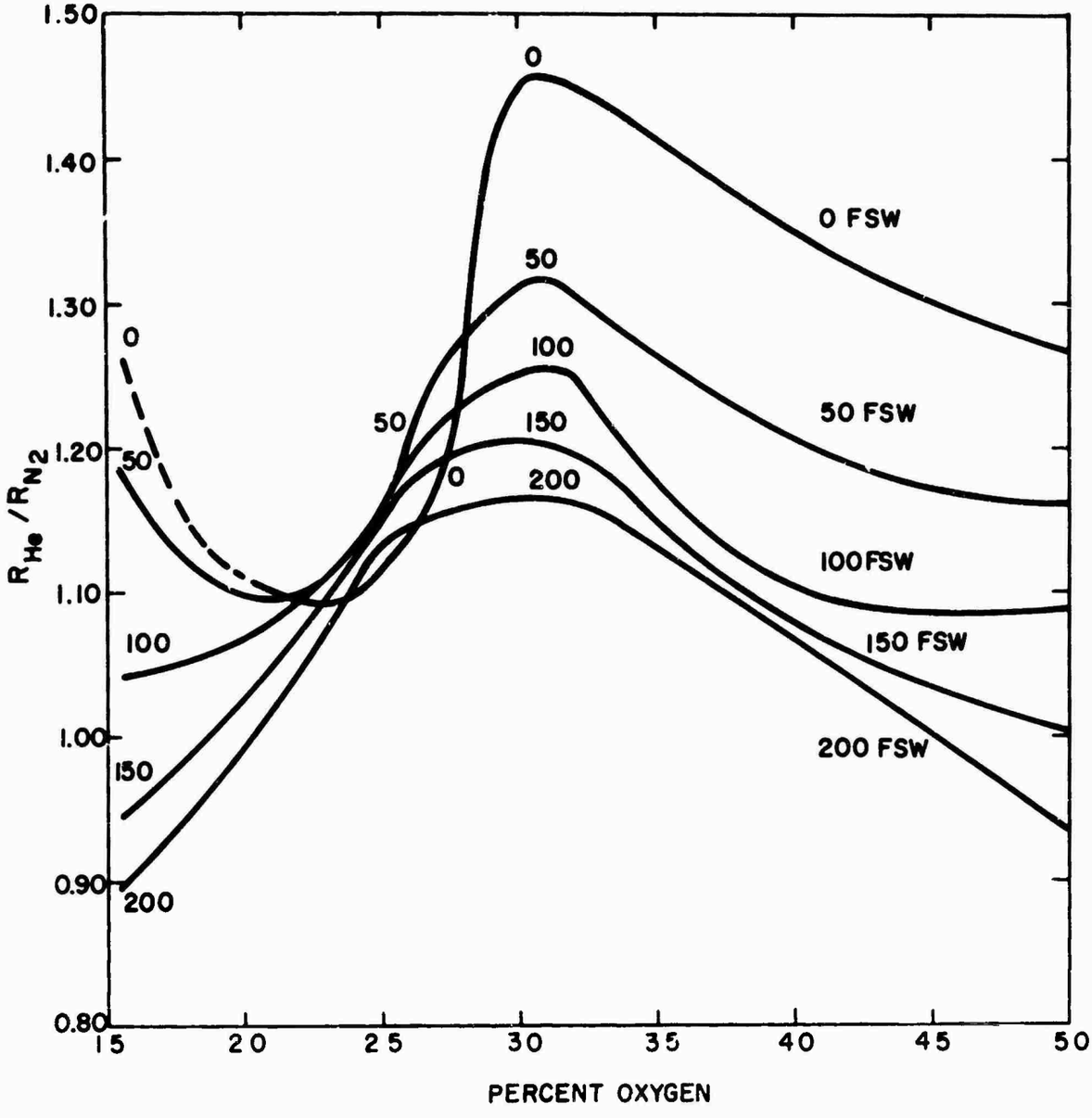


Figure 1. Relative effect of helium and nitrogen as oxygen diluents on the rate of combustion of paper strips at an angle of 45°

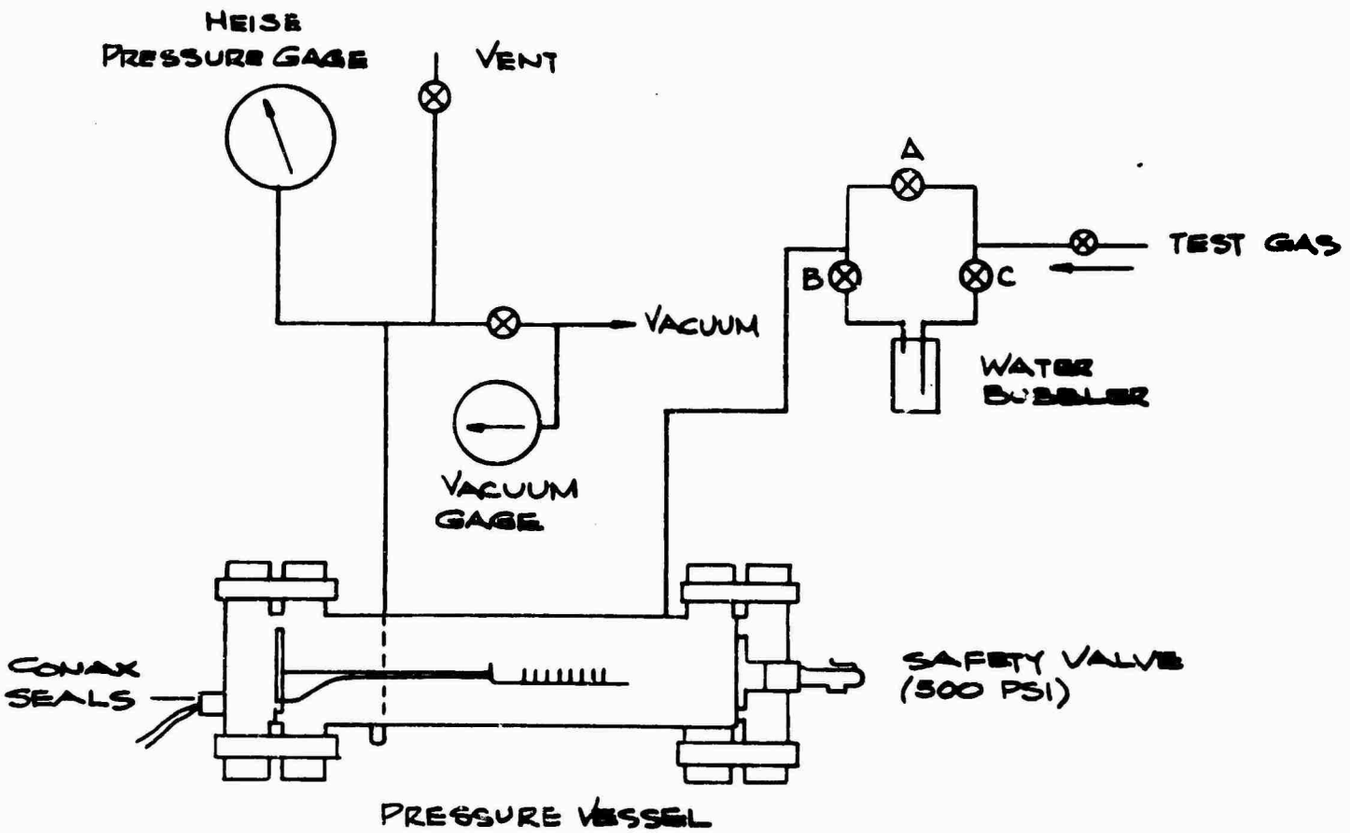


Figure 2. Diagram of four-inch pressure vessel and auxiliary equipment

Fig. 2

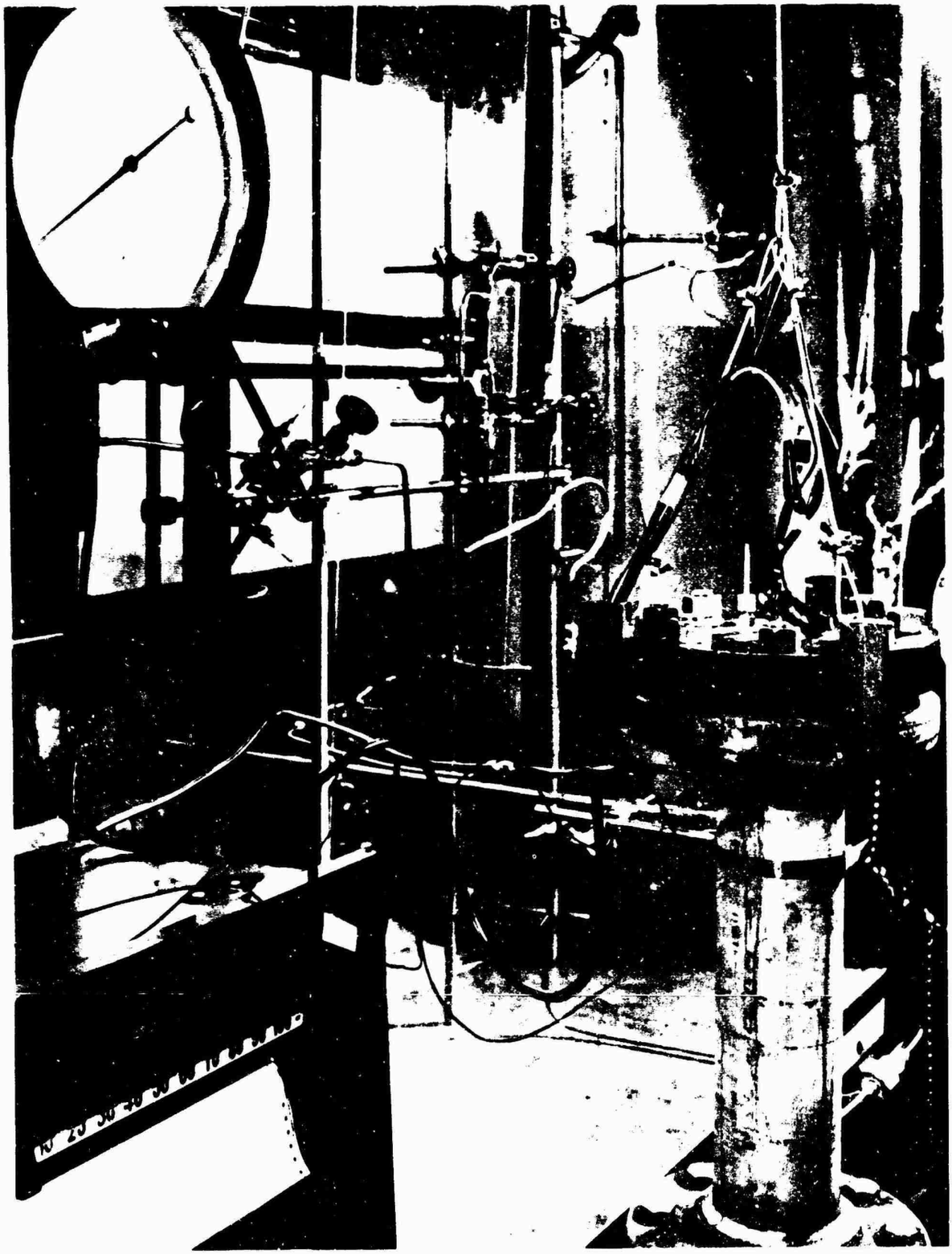


Figure 3. Photograph of four-inch pressure vessel and auxiliary equipment

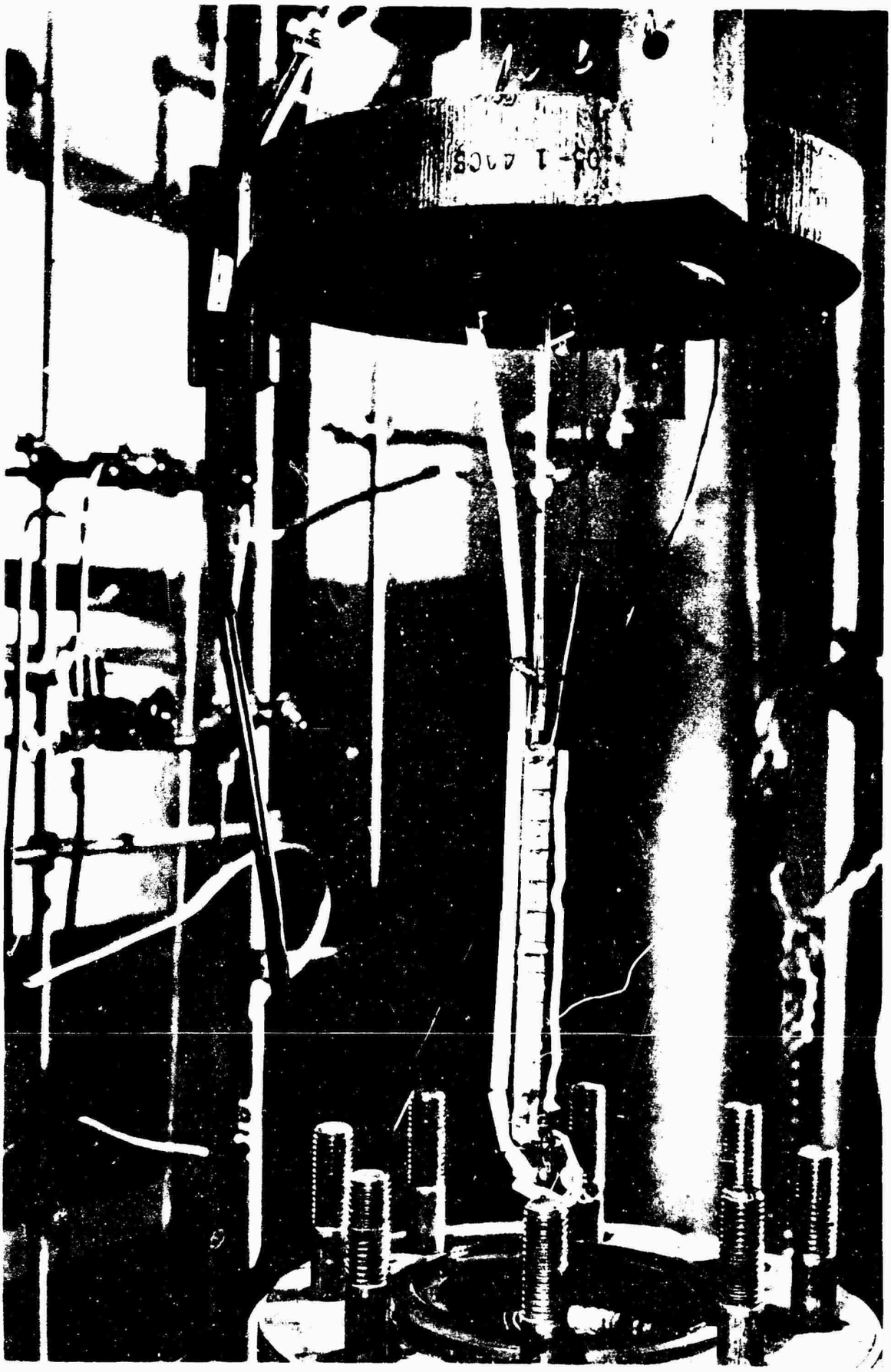


Figure 4. Photograph of upper flange, sample holder, and top of the four-inch vessel

Fig. 4

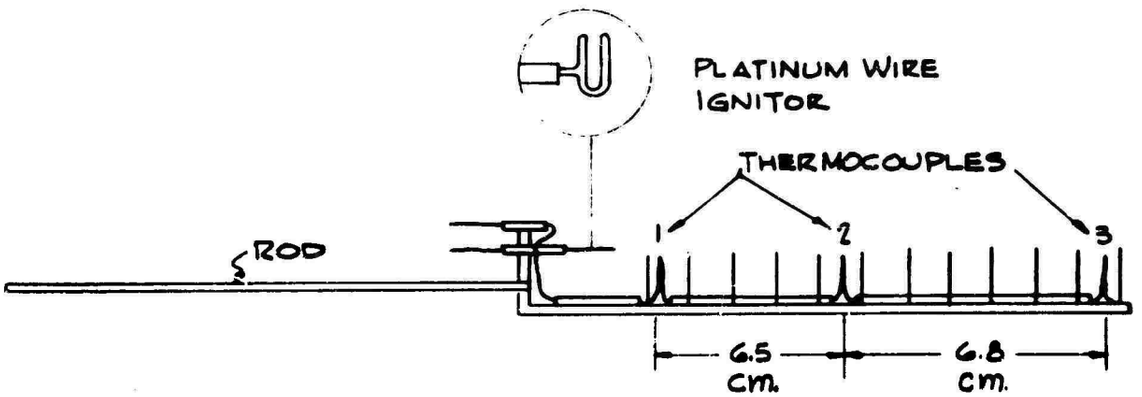


Figure 5. Sketch of sample holder for four-inch vessel

Fig. 5

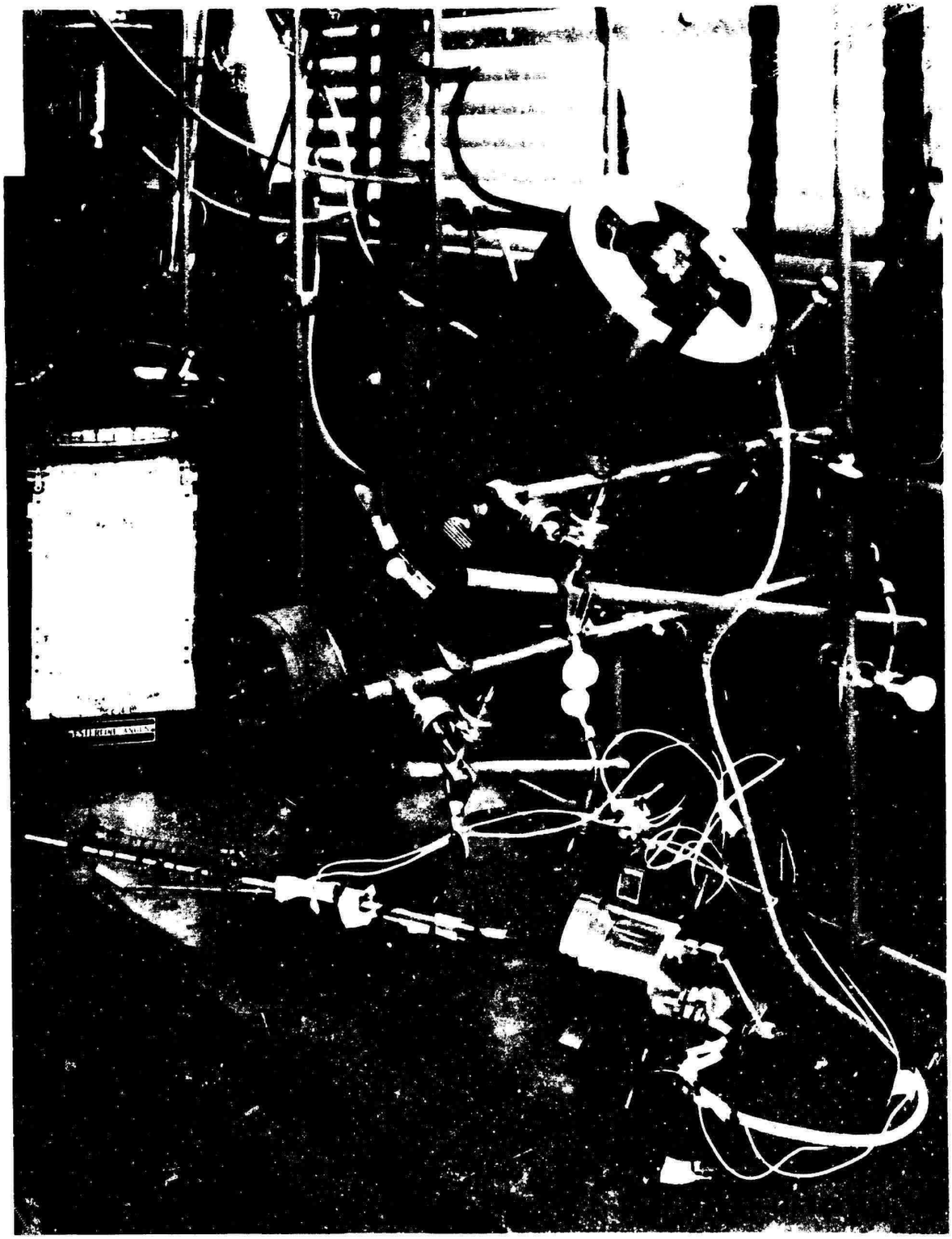


Figure 6. Photograph of the six-inch pressure vessel and its closure and sample holder

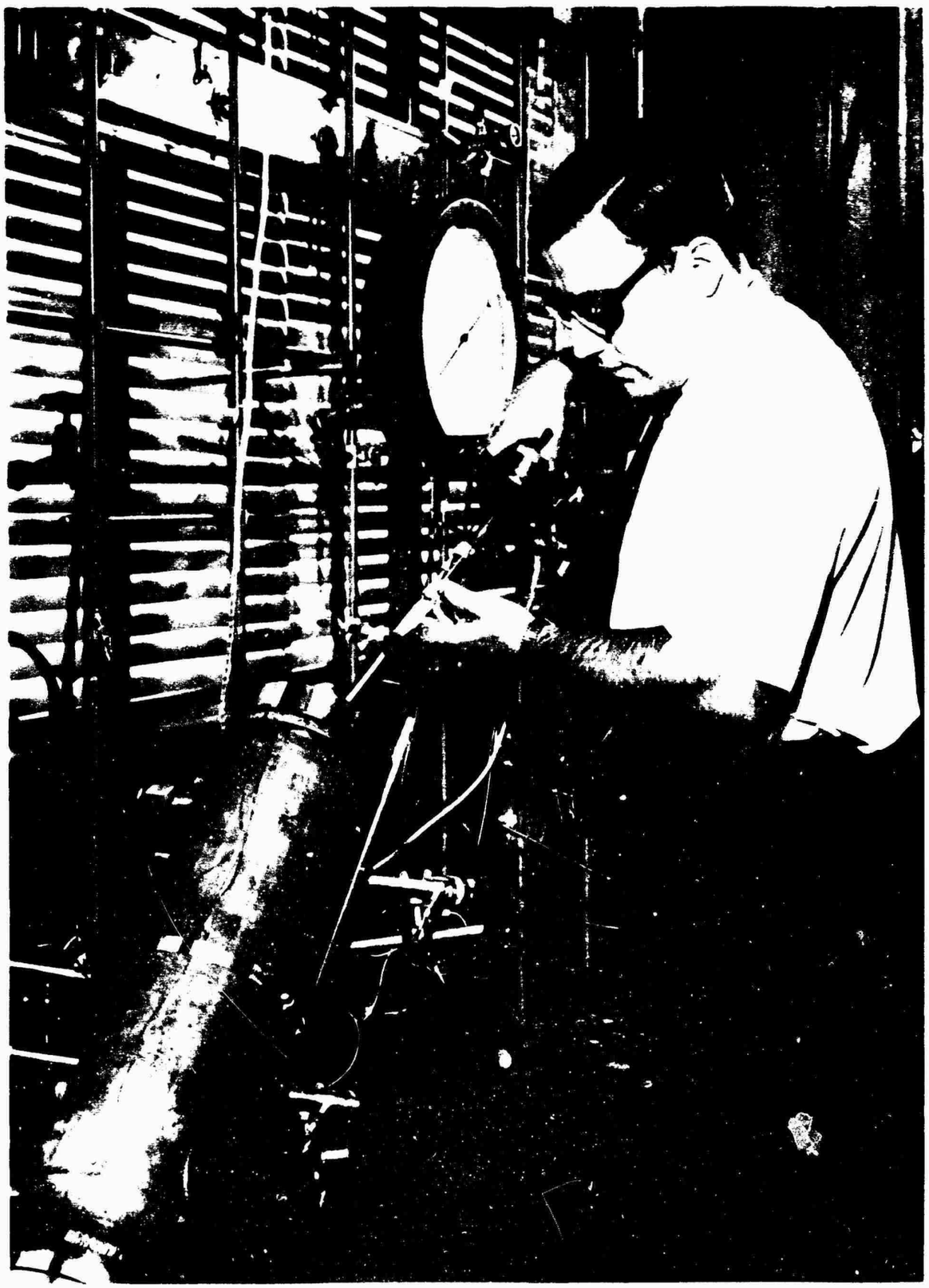


Figure 7. Robert Meierer inserting a sample into the six-inch pressure vessel

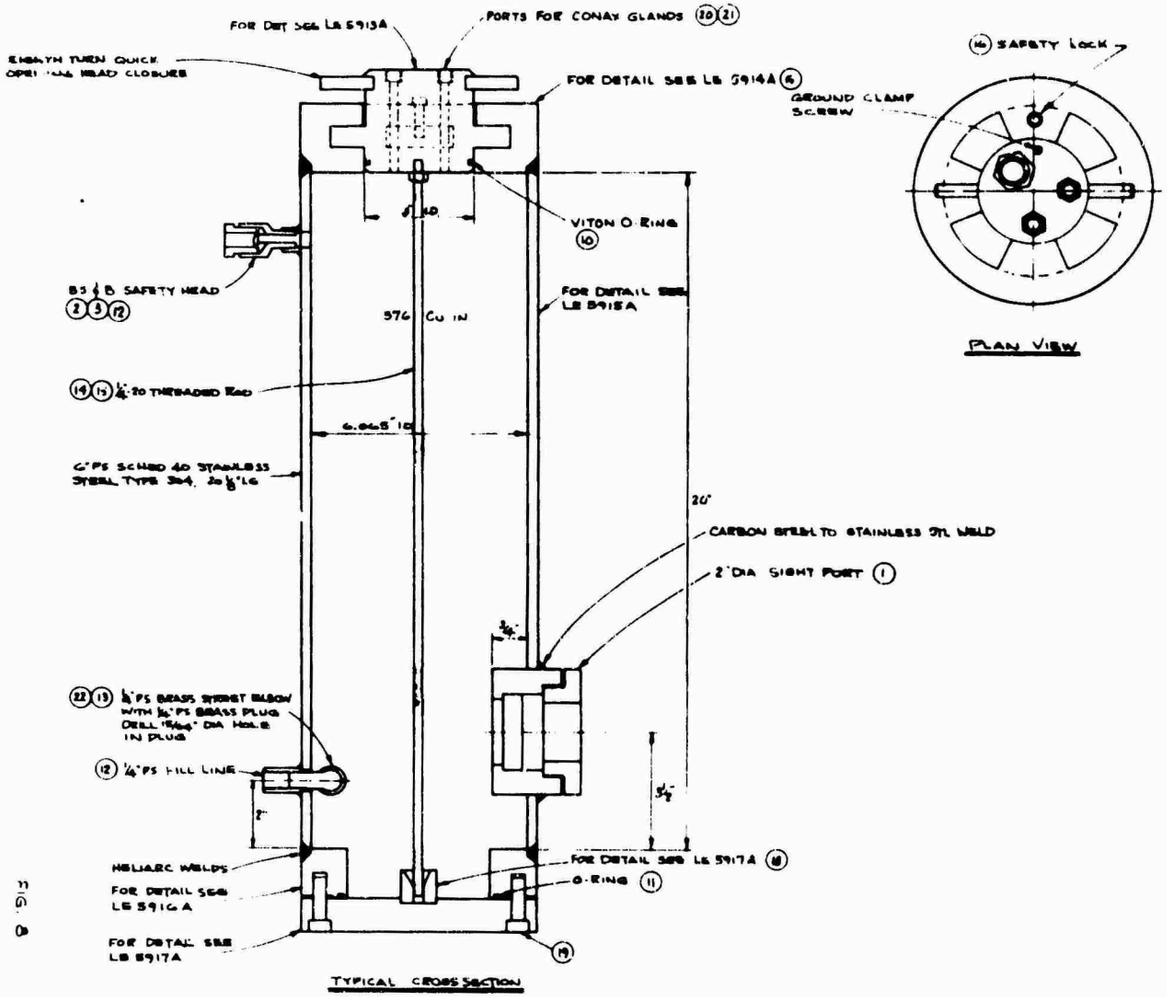
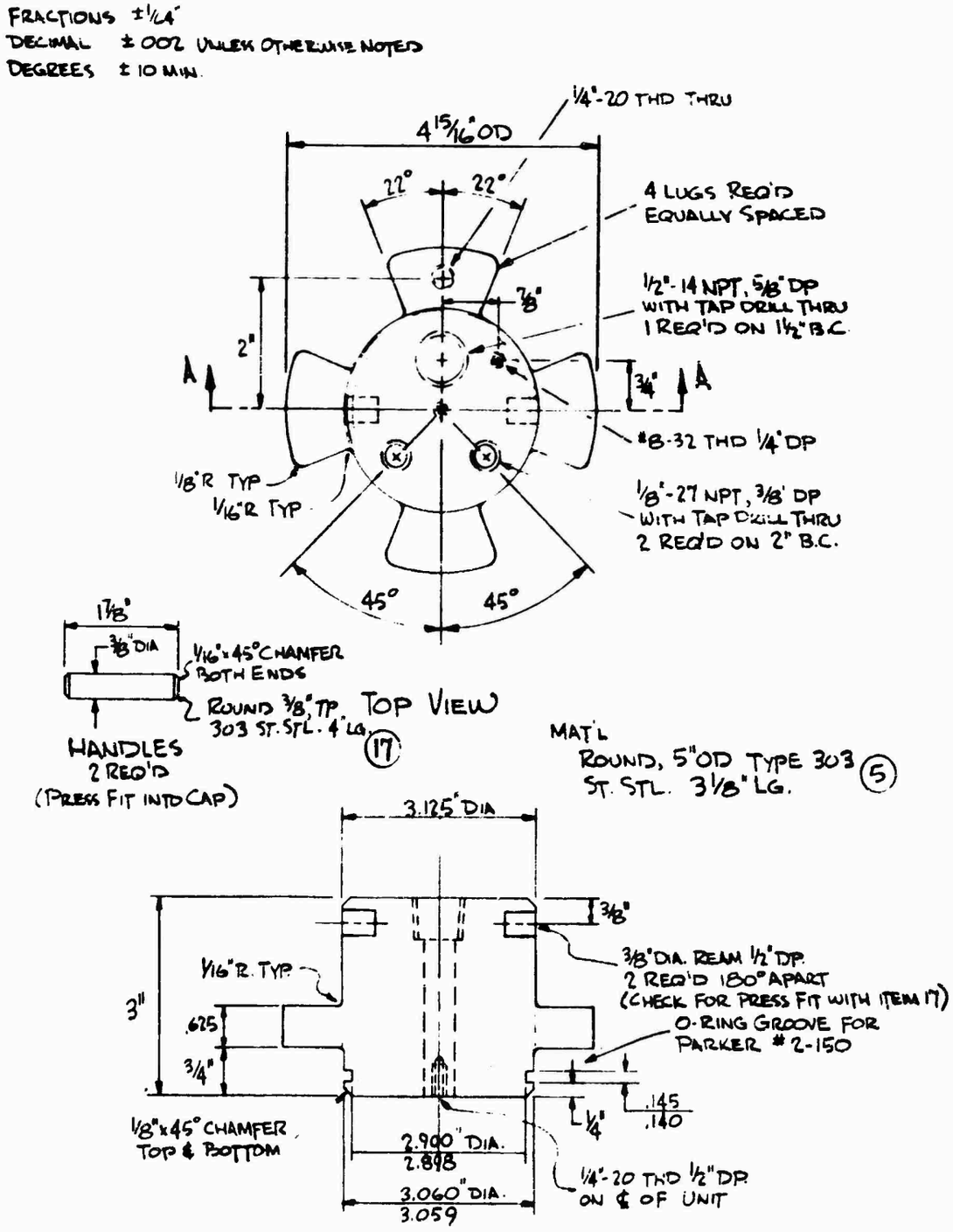


FIG. 8

FIGURE 8. 600 PSI @ 70°F PRESSURE VESSEL

BILL OF MATERIALS

ITEM No.	No. REQ'D.	DESCRIPTION
1	1	SIGHT PORT, 2" DIA. "PRESSURE PRODUCTS CO., 600# WORKING PRESS., VITON PACKING, SIMILAR TO SD-4D7-69-1 EXCEPT
		FOR PRESSURE RATING, CARBON STEEL CONSTRUCTION
2	1	SAFETY HEAD, "BS & B #JS ST. STL. INLET, STEEL OUTLET & RING, 1/4" MPT INLET, FREE OUTLET
3	2	RUPTURE DISC, 600#, TO FIT "JS SAFETY HD. MATERIAL ALUMINUM
5	1	ROUND, 5" O.D. TYPE 303 STAINLESS STEEL × 3 1/8" LG
6	1	PLATE, 2" THK, TYPE 304 STAINLESS STEEL × 7" DIA.
7	1	PLATE, 1 1/2" THK, TYPE 304 STAINLESS STEEL × 7" DIA.
8	1	PLATE, 1" THK, TYPE 304 STAINLESS STEEL × 7" DIA.
9	1	PIPE, 6" P.S. TYPE 304 SEAMLESS ST. STL. SCHED 40 × 20 1/2"
10	2	O-RING, PARKER #2-150 VITON A MATERIAL
11	2	O-RING, PARKER #2-244 VITON A MATERIAL
12	2	COUPLING, 1/4" P.S. TYPE 304 STAINLESS STEEL, 1000 PSI W.P.
13	1	STREET ELBOW, 1/4" P.S. BRASS, 90°
14	1	THREADED ROD, 1/4"-20 CAD. PLATED STEEL × 24" LG.
15	1	HEX NUT, 1/4-20 BRASS
16	1	SOCKET HEAD CAPSCREW 1/4"-20 STEEL 1" LG.
17	1	ROUND, 3/8" O.D. TYPE 303 STAINLESS STL. × 4" LG.
18	1	ROUND, 1" O.D. TYPE 304 STAINLESS STL. × 1 1/8" LG.
19	12	SOCKET HD. CAPSCREW, 3/8"-16 STAINLESS STL. × 1 1/4" LG.
20	2	CONAX GLAND, 1/8" P.S.
21	1	CONAX GLAND, 1/2" P.S.
22	1	BRASS PLUG, 1/4" P.S.
		Figure 8 (continued). Six-inch pressure vessel
		Fig. 8 (cont'd)



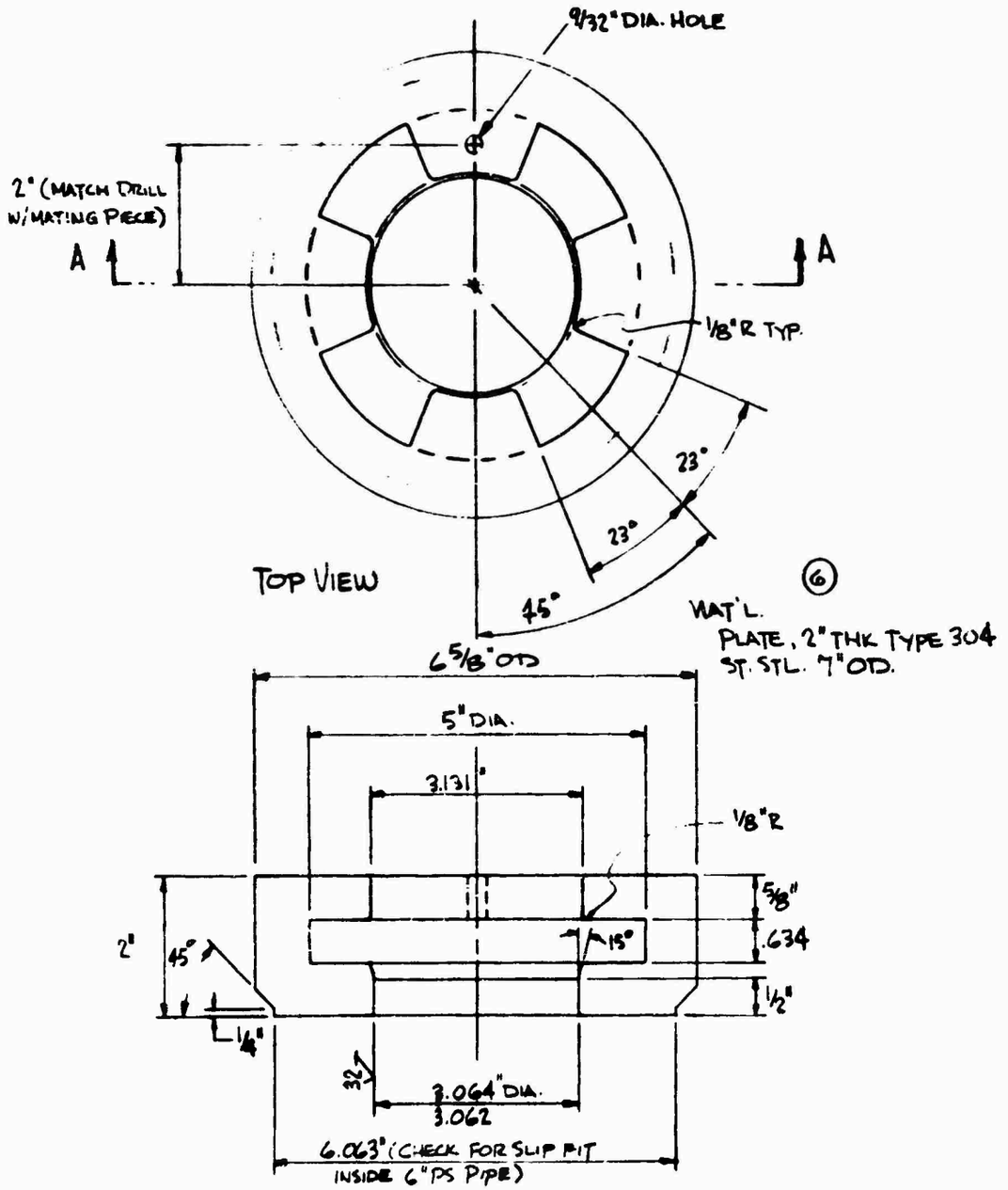
SECTION "A-A"

CAP DETAIL FOR 6000PSI VESSEL

P. No. 11-771
wob 4.20.66
AES 4/21/66
LE 5913 A

Figure 9. Six-inch pressure vessel. Cap detail

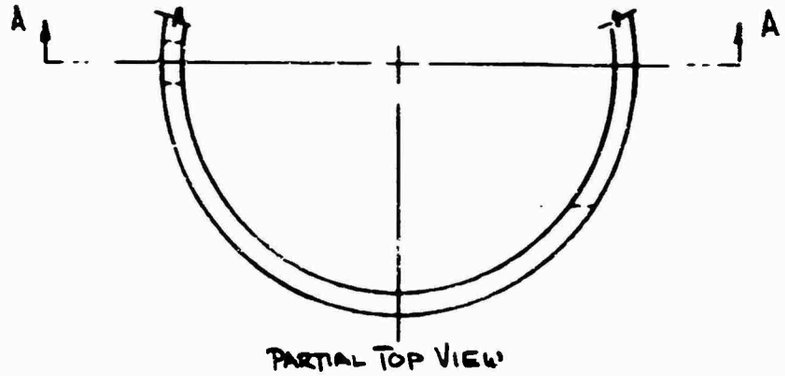
FRACTIONS ± 1/64"
DECIMAL ±.002 UNLESS OTHERWISE NOTED
DEGREES ±1D MIN.

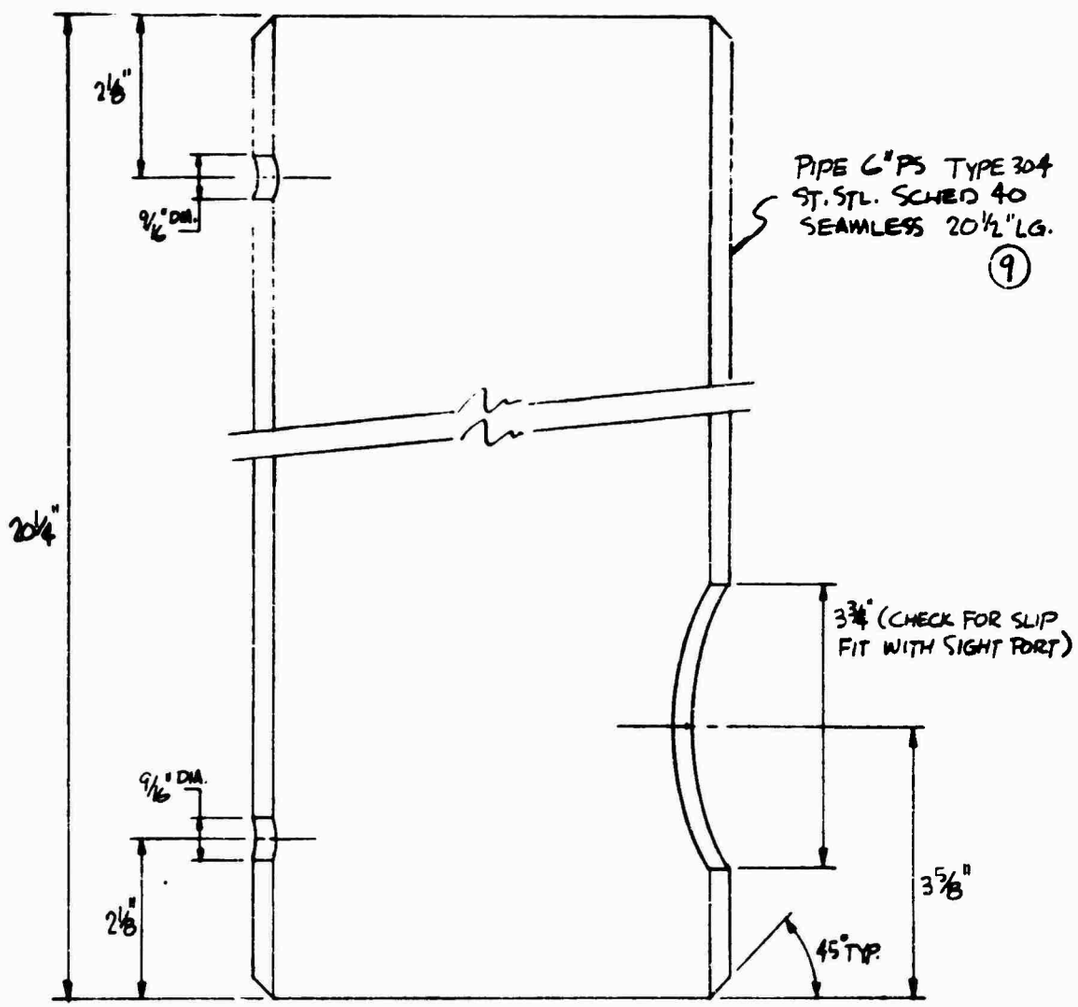


SECTION A-A
TOP BODY DETAIL FOR 6000PSI VESSEL

P No 11-771
WOB 4-20-66
MFS 4/21/66
Fig. 10
LE 5914 A

Figure 10. Six-inch pressure vessel. Top body detail





SECTION "A-A"
600PSI VESSEL BODY

P.No. 11-771
w.o. 4.21.66
RB 4/21/66
LE5915A

Figure 11. Six-inch pressure vessel. Vessel body detail

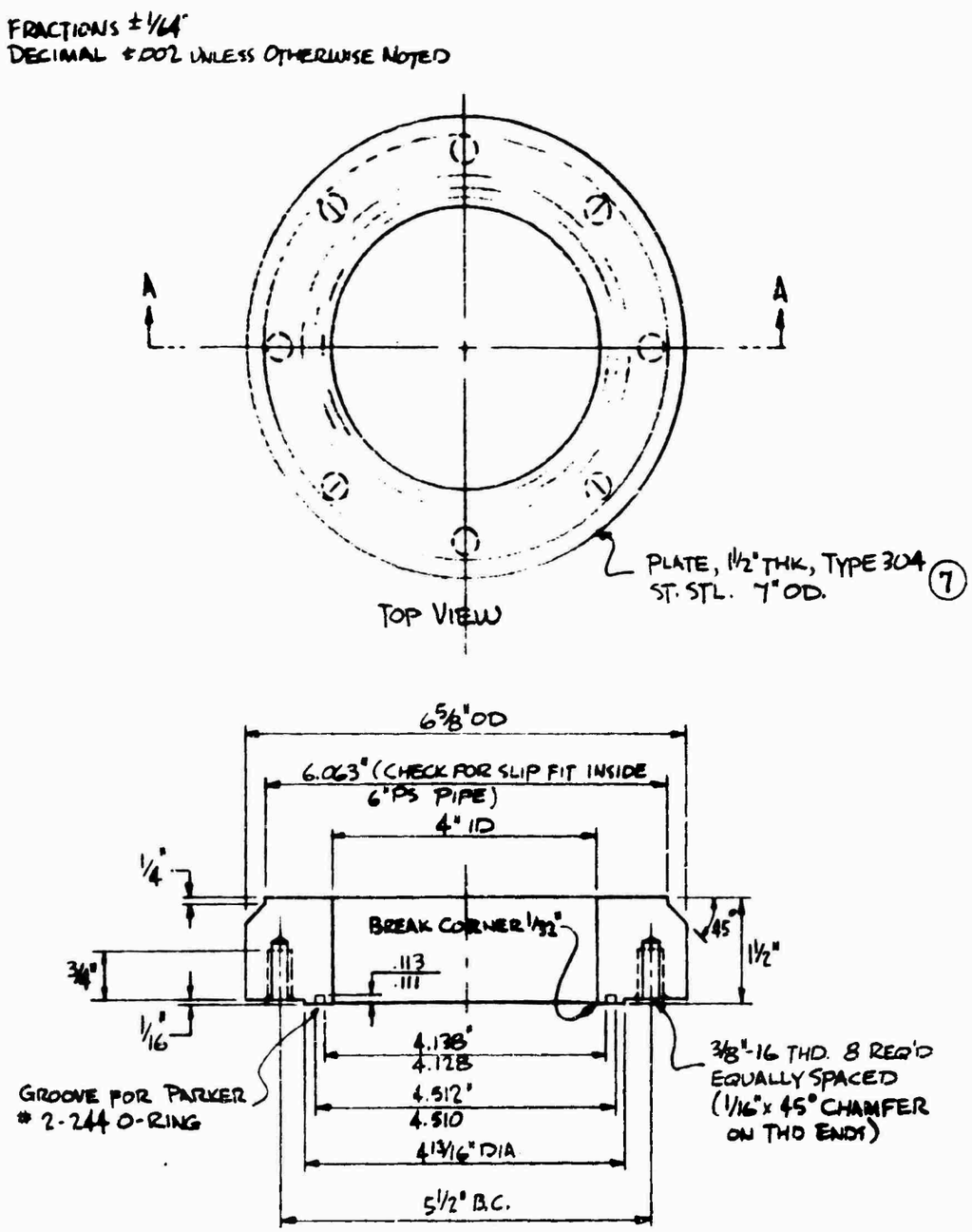


Figure 12. Six-inch pressure vessel. Bottom flange ring detail

P.No. 11-771
wob 4-21-66
ATJ 4/21/66
LE5916A Fig. 12

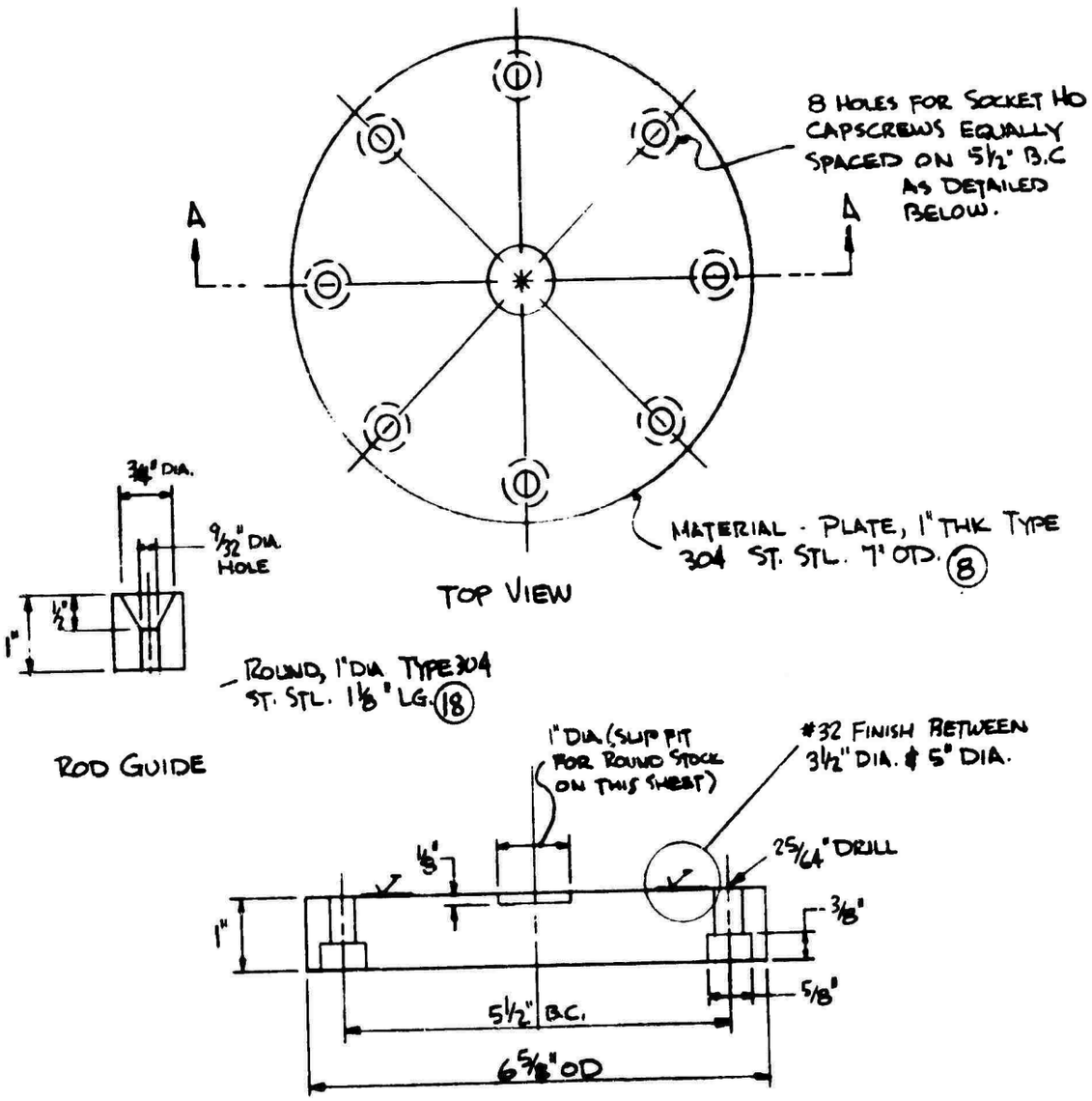


Figure 13. Six-inch pressure vessel. Blind flange detail

P.No. 11-771
WO 6 4.21.66 AFS 4/21/66
LE5917A
Fig. 13

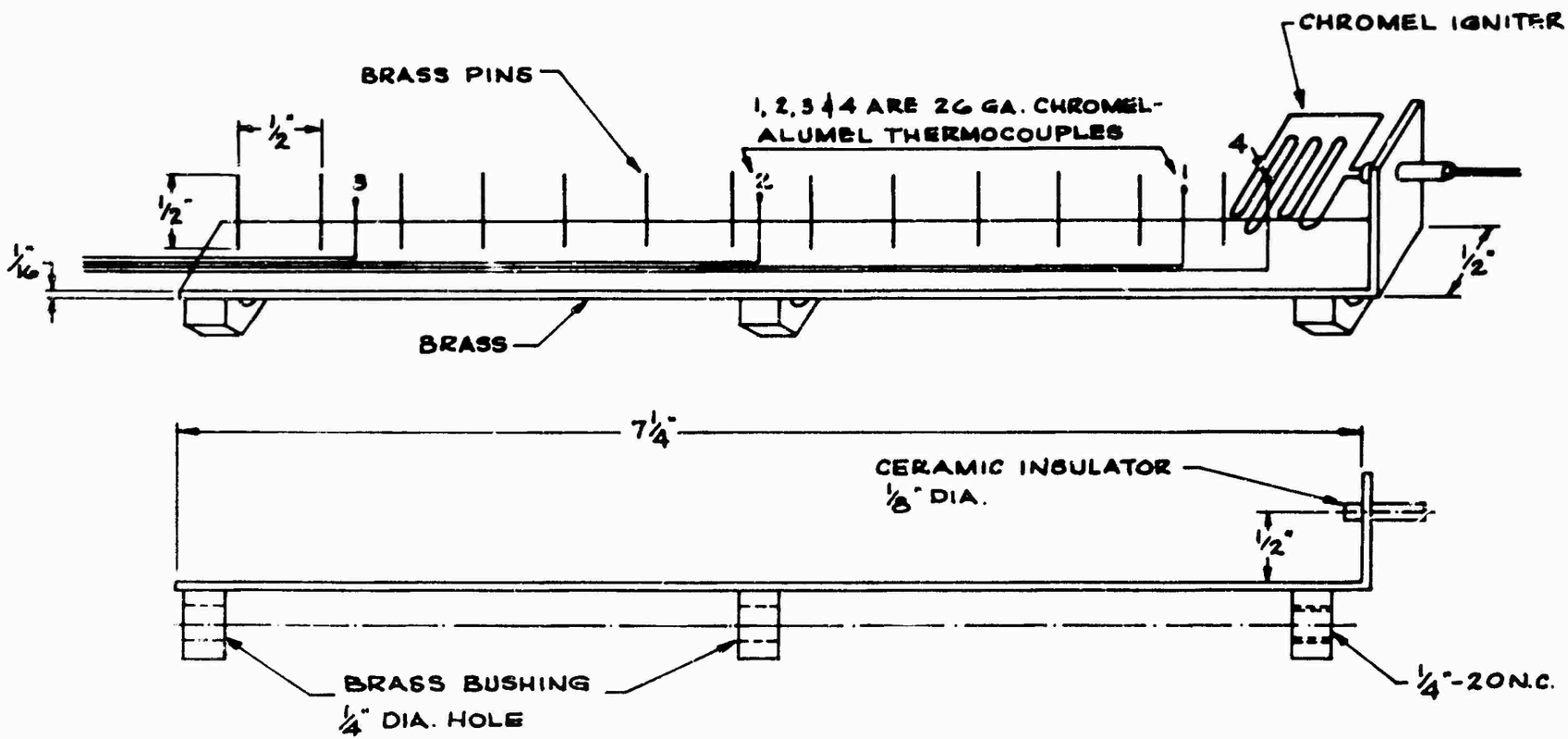


Figure 14. Sketch of sample holder used in six-inch vessel

Fig. 14

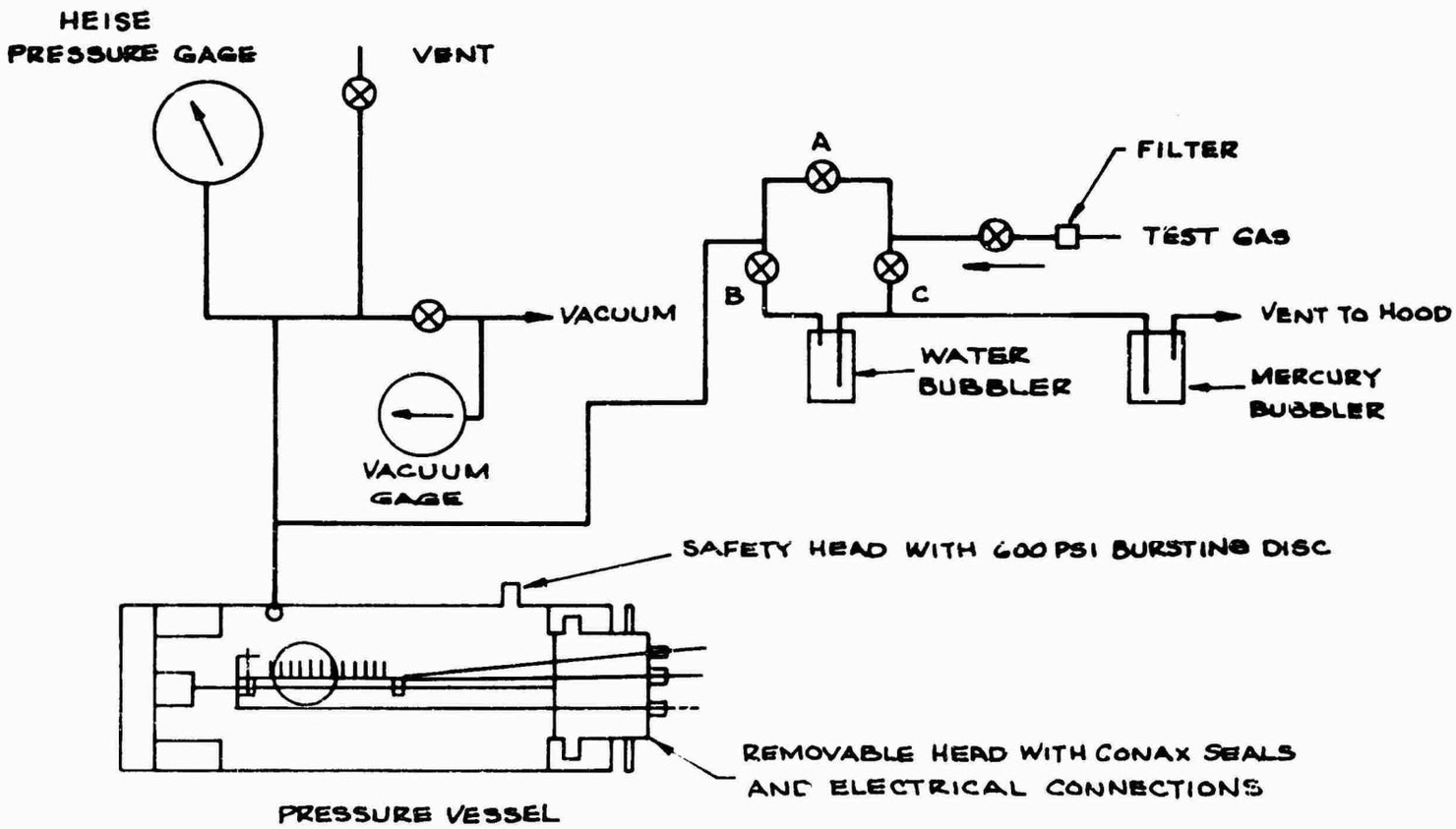


Figure 15. Diagram of six-inch pressure vessel and auxiliary equipment

Fig. 15

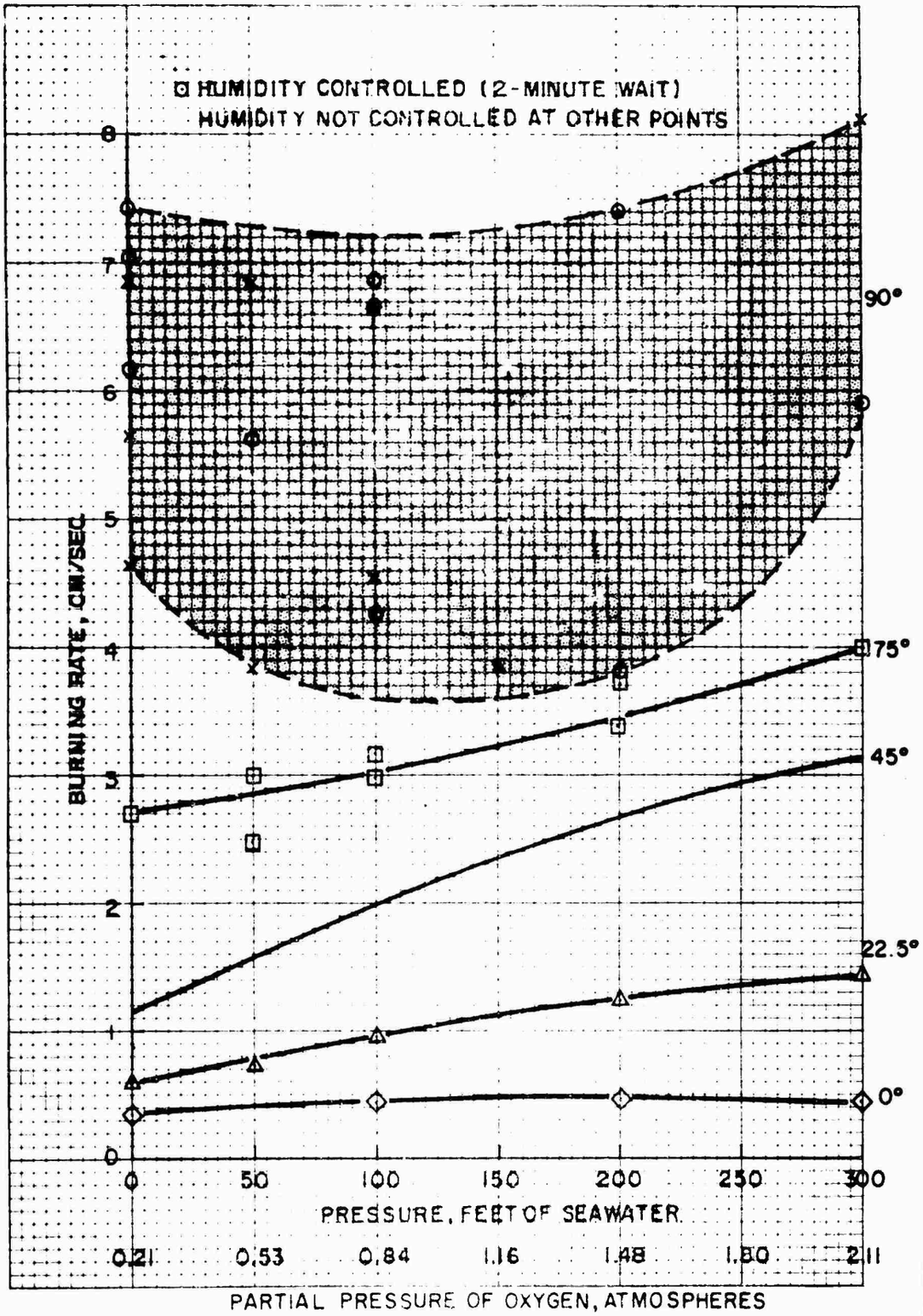


Figure 16. Variation with pressure of burning rate of filter paper strips held at various angles in air, 0 to 300 Feet

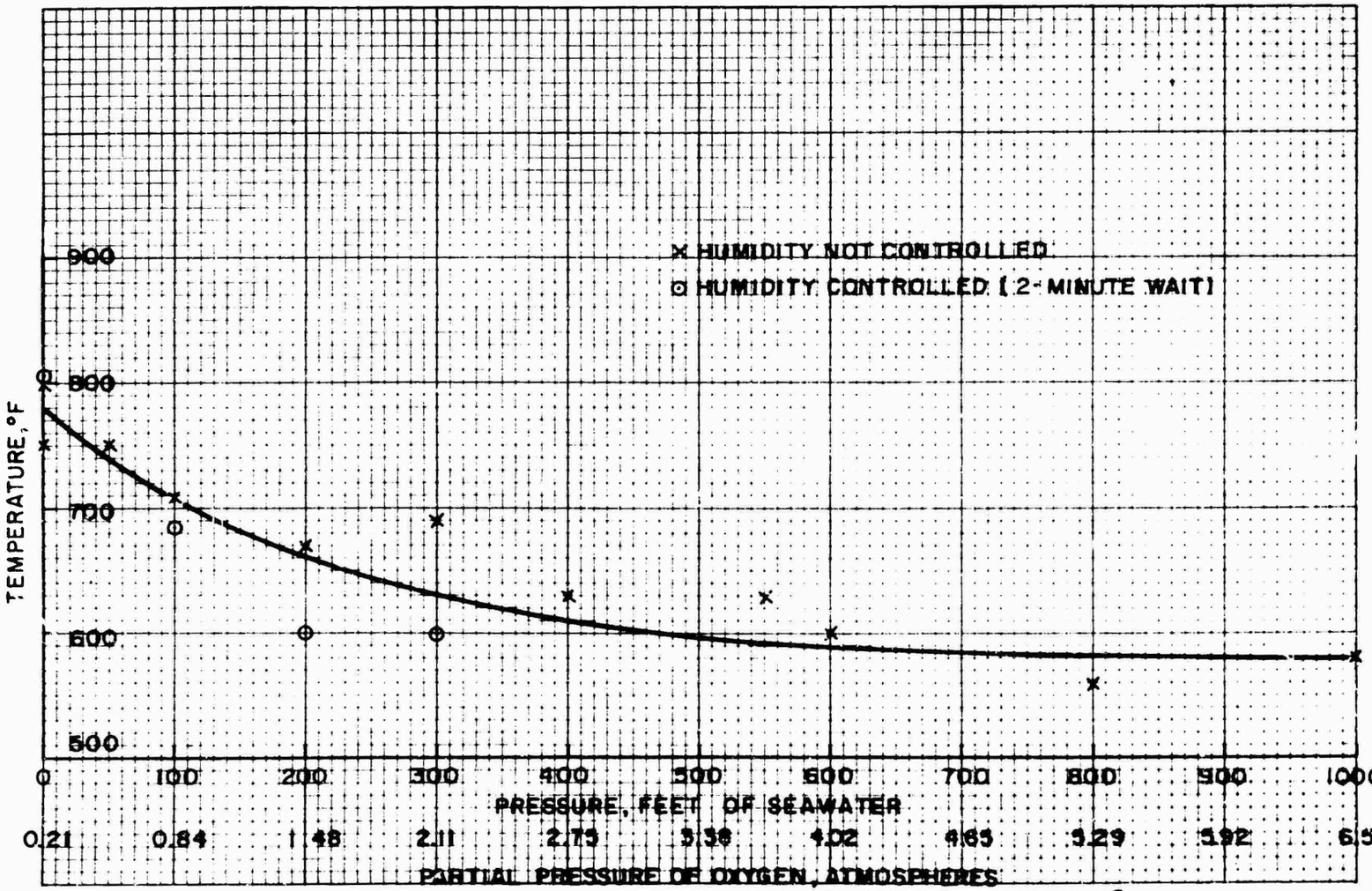


Figure 17. Variation with pressure of the ignition temperature of filter paper strips at an angle of 45° in compressed air

Fig. 17

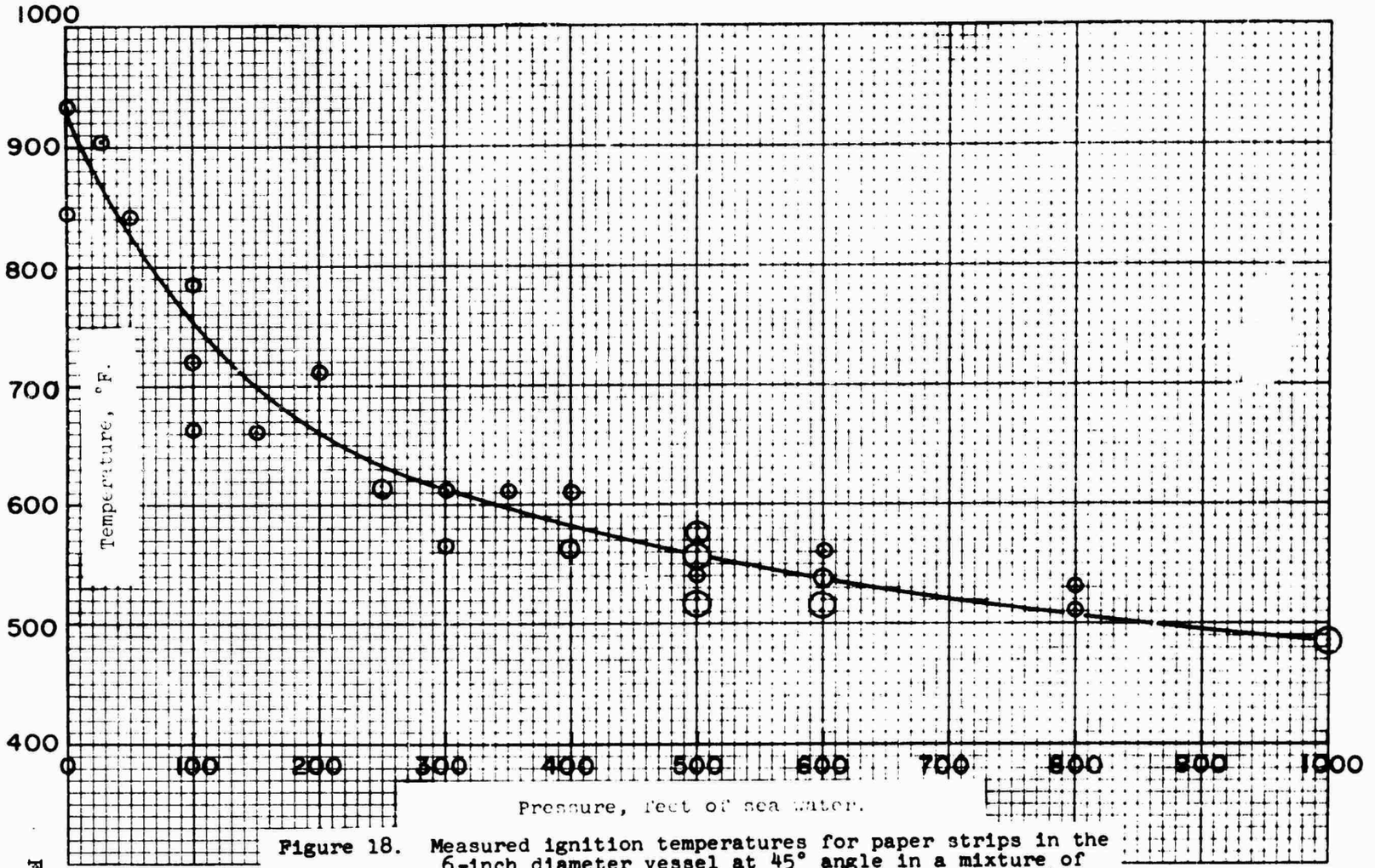


Figure 18. Measured ignition temperatures for paper strips in the 6-inch diameter vessel at 45° angle in a mixture of 22.5% oxygen and 77.5% nitrogen (simulated air)

Fig. 18

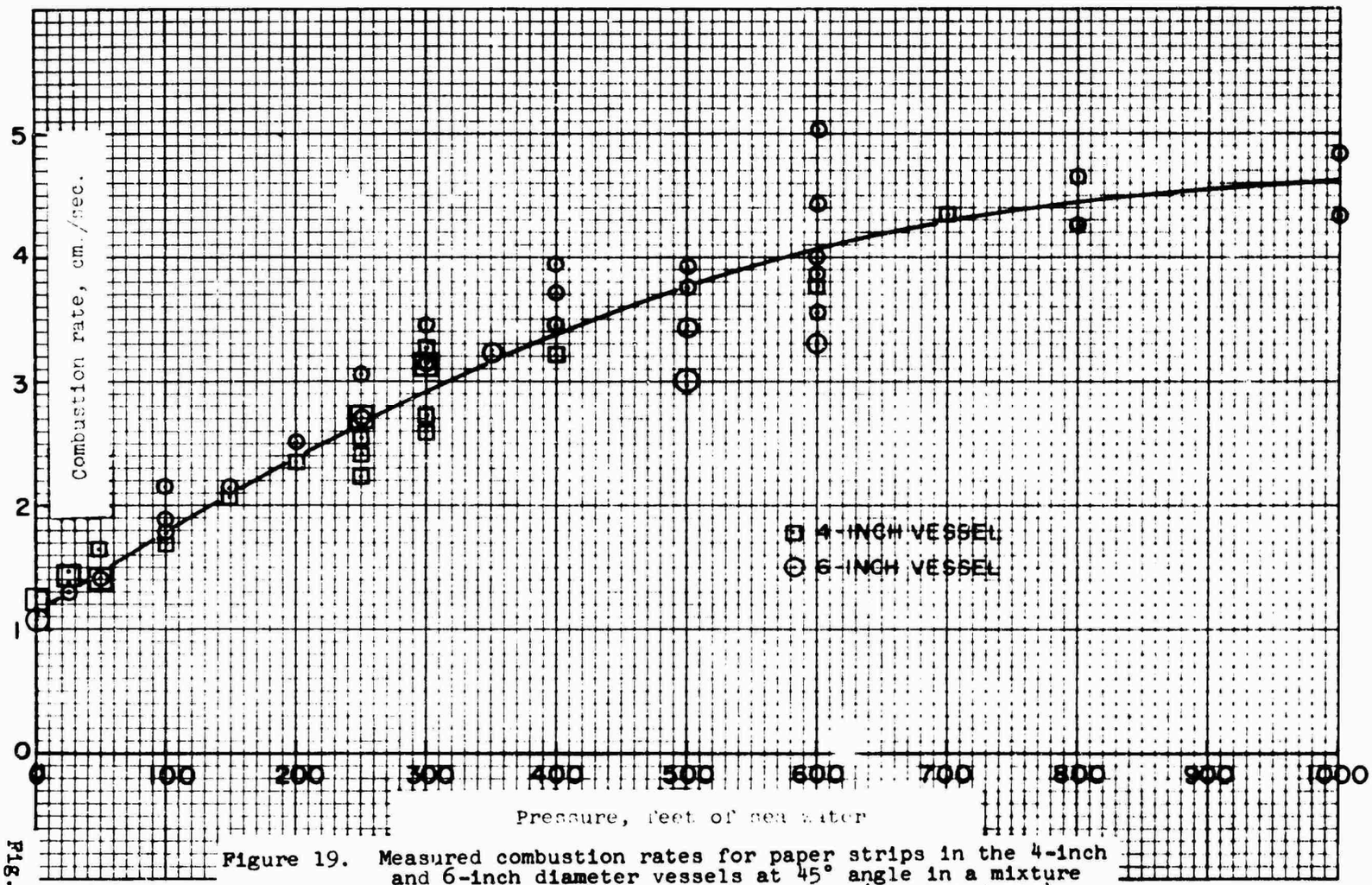


Fig. 19

Figure 19. Measured combustion rates for paper strips in the 4-inch and 6-inch diameter vessels at 45° angle in a mixture of 22.5% oxygen and 77.5% nitrogen (simulated air)

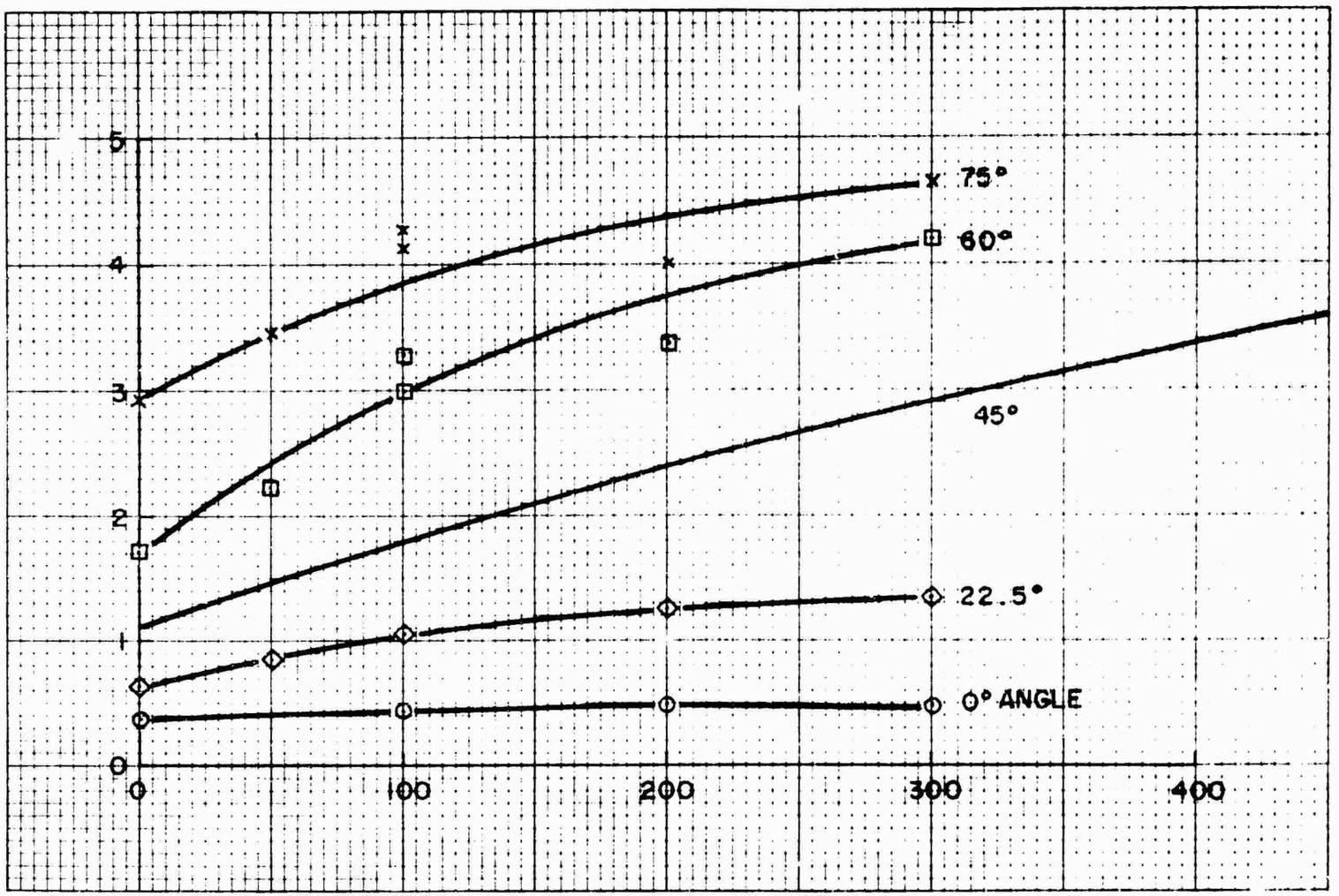


Figure 20. Experimental results for the burning of filter paper strips at various angles in simulated compressed air

Fig. 20

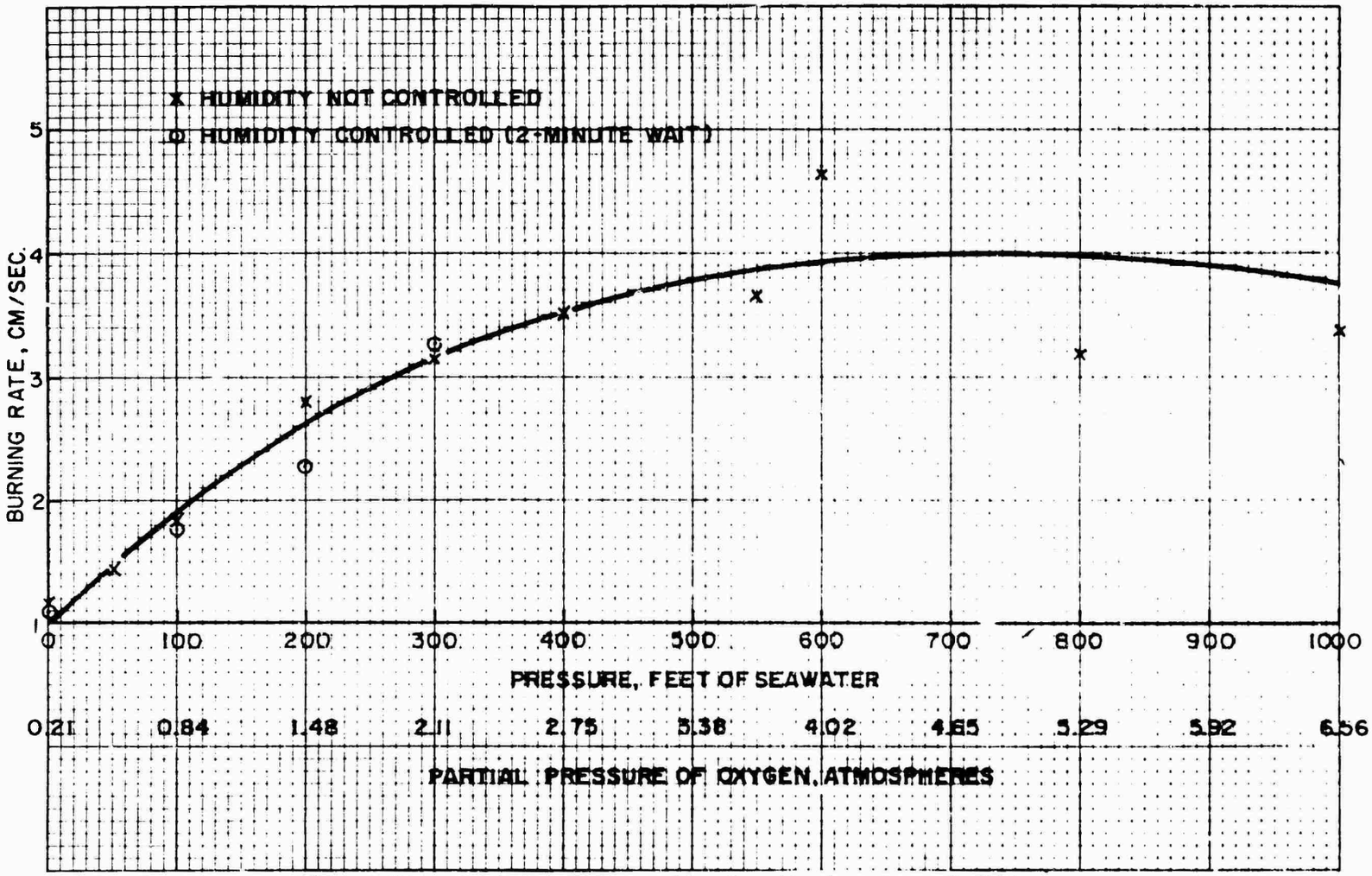


Figure 21. Experimental results for the burning of filter paper strips at an angle of 45° in compressed air

Fig. 21

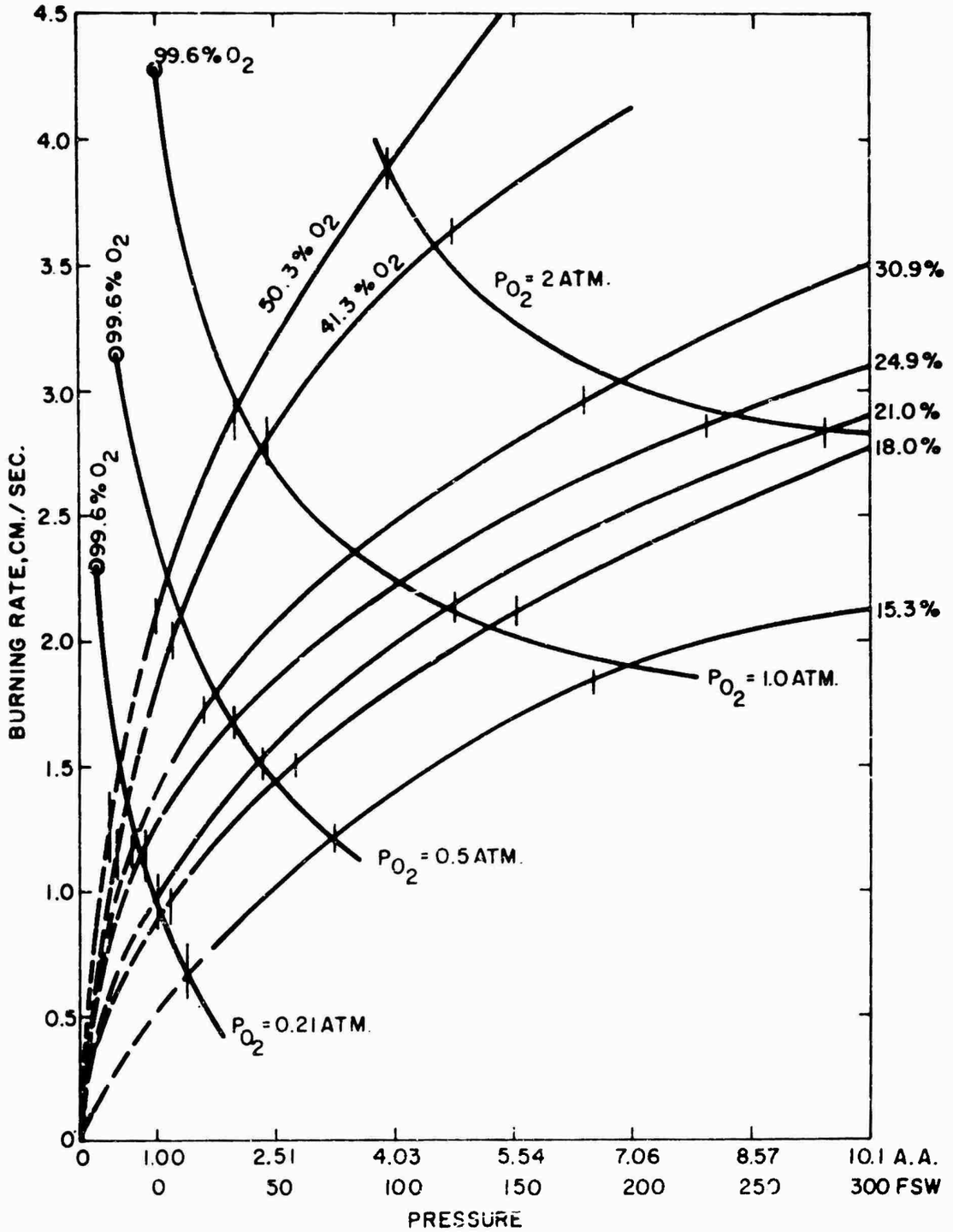


Figure 22. Experimental results for the burning of filter paper strips at an angle of 45° in N_2-O_2 mixtures

Fig. 22

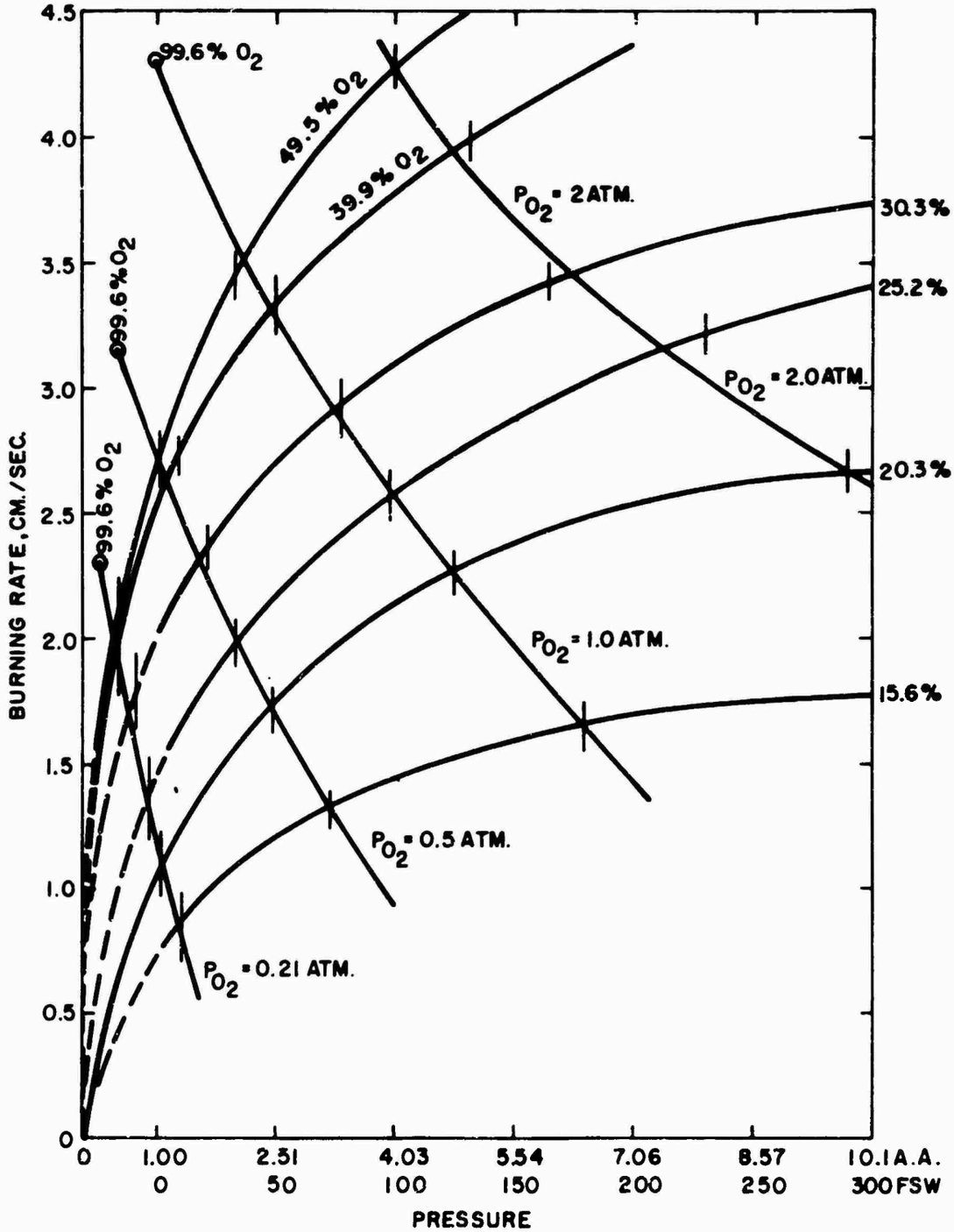


Figure 23. Experimental results for the burning of filter paper strips at an angle of 45° in N_2-O_2 mixtures

Fig. 23

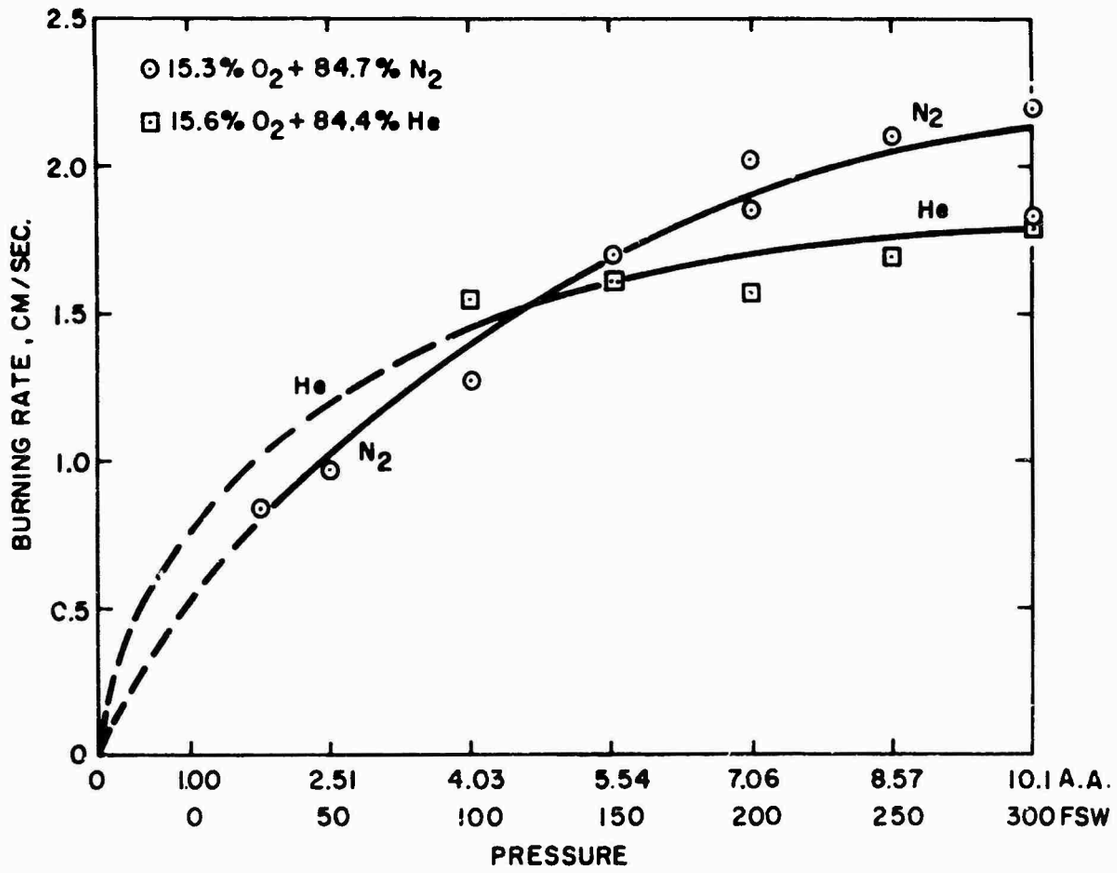


Figure 24. Experimental comparison of helium with nitrogen as oxygen diluents in mixtures containing about 15% oxygen

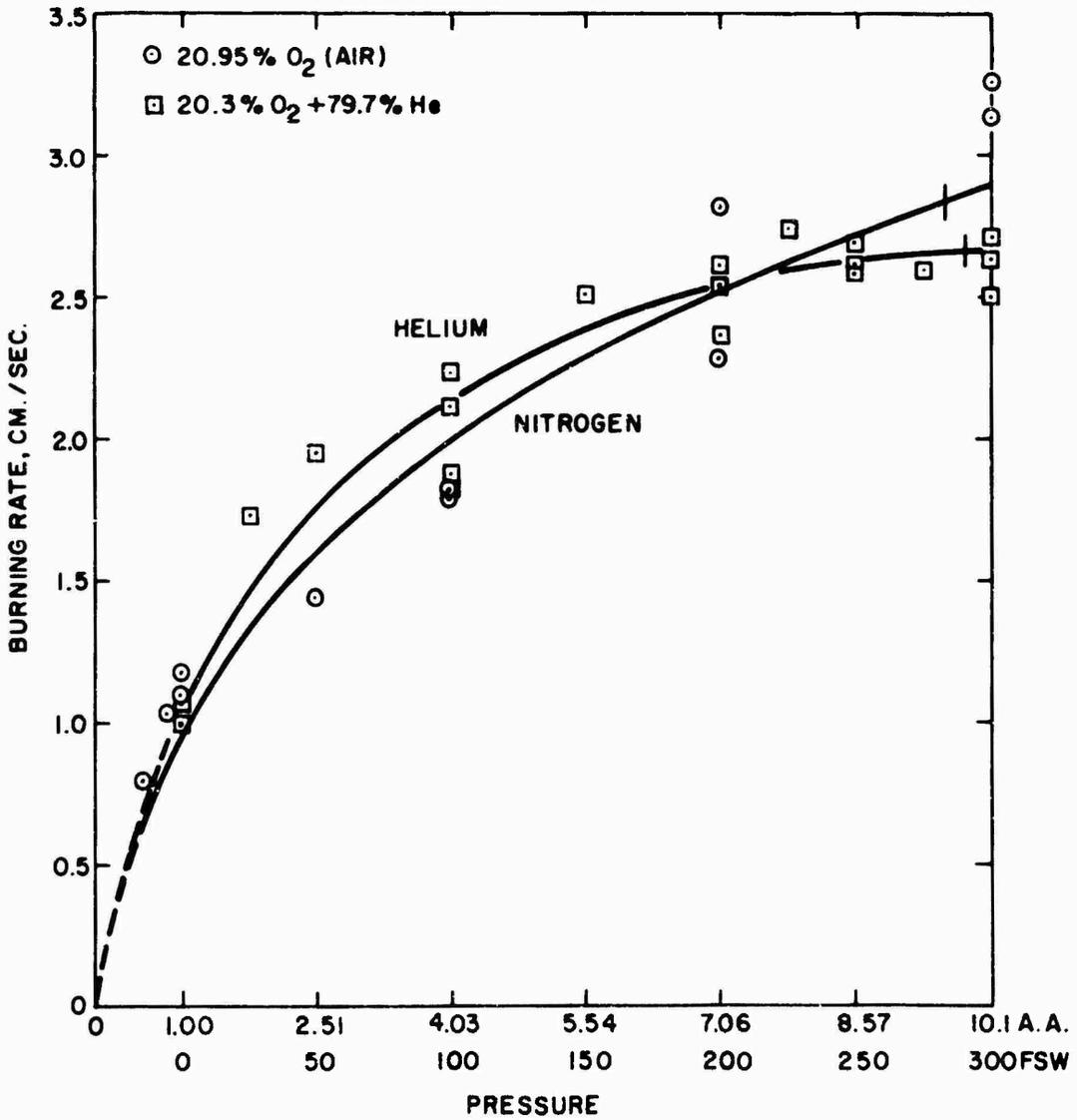


Figure 25. Experimental comparison of helium with nitrogen as oxygen diluents in mixtures containing about 21% oxygen

Fig. 25

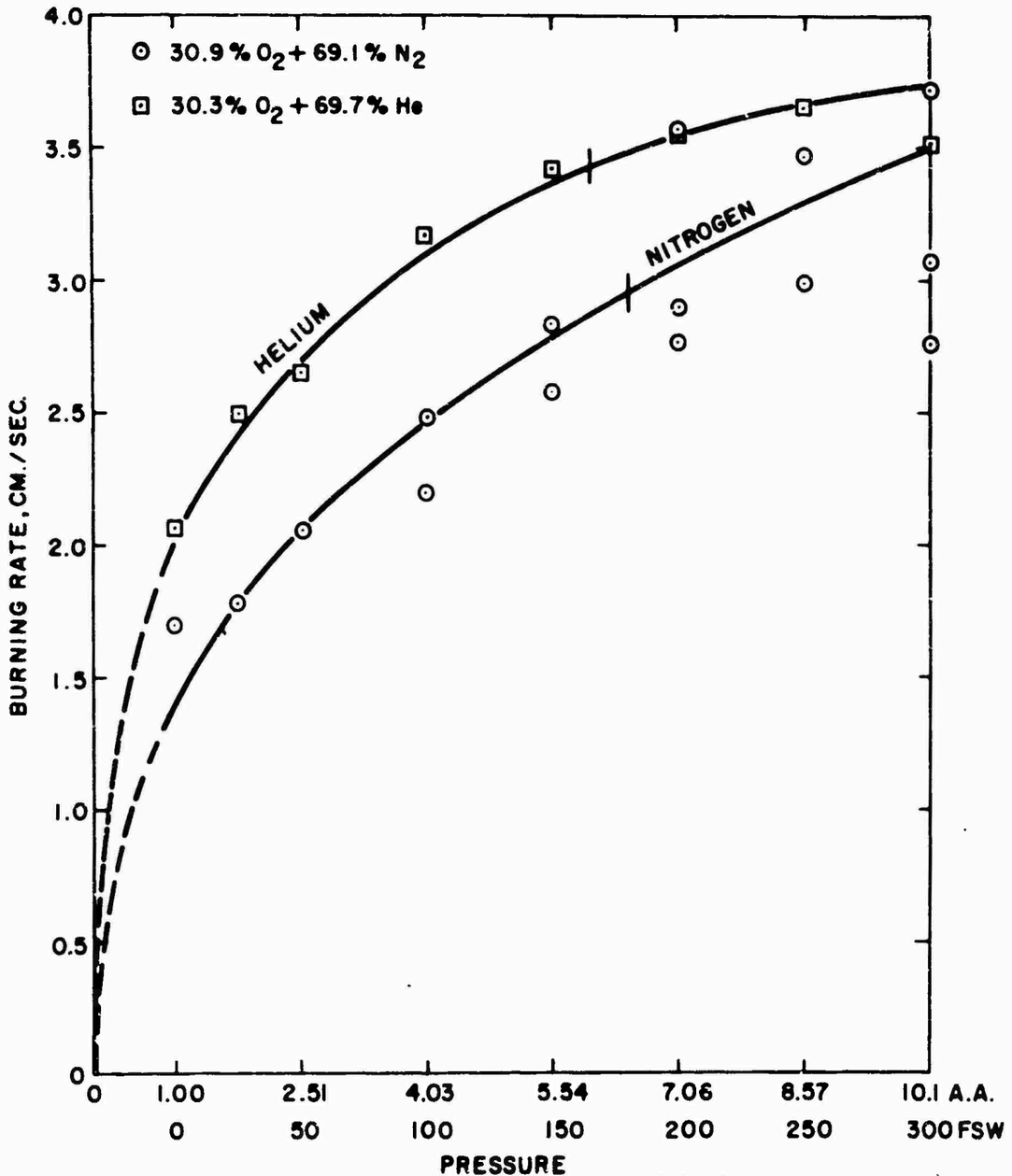


Figure 26. Experimehtal comparison of helium with nitrogen as oxygen diluents in mixtures containing about 30% oxygen

Fig. 26

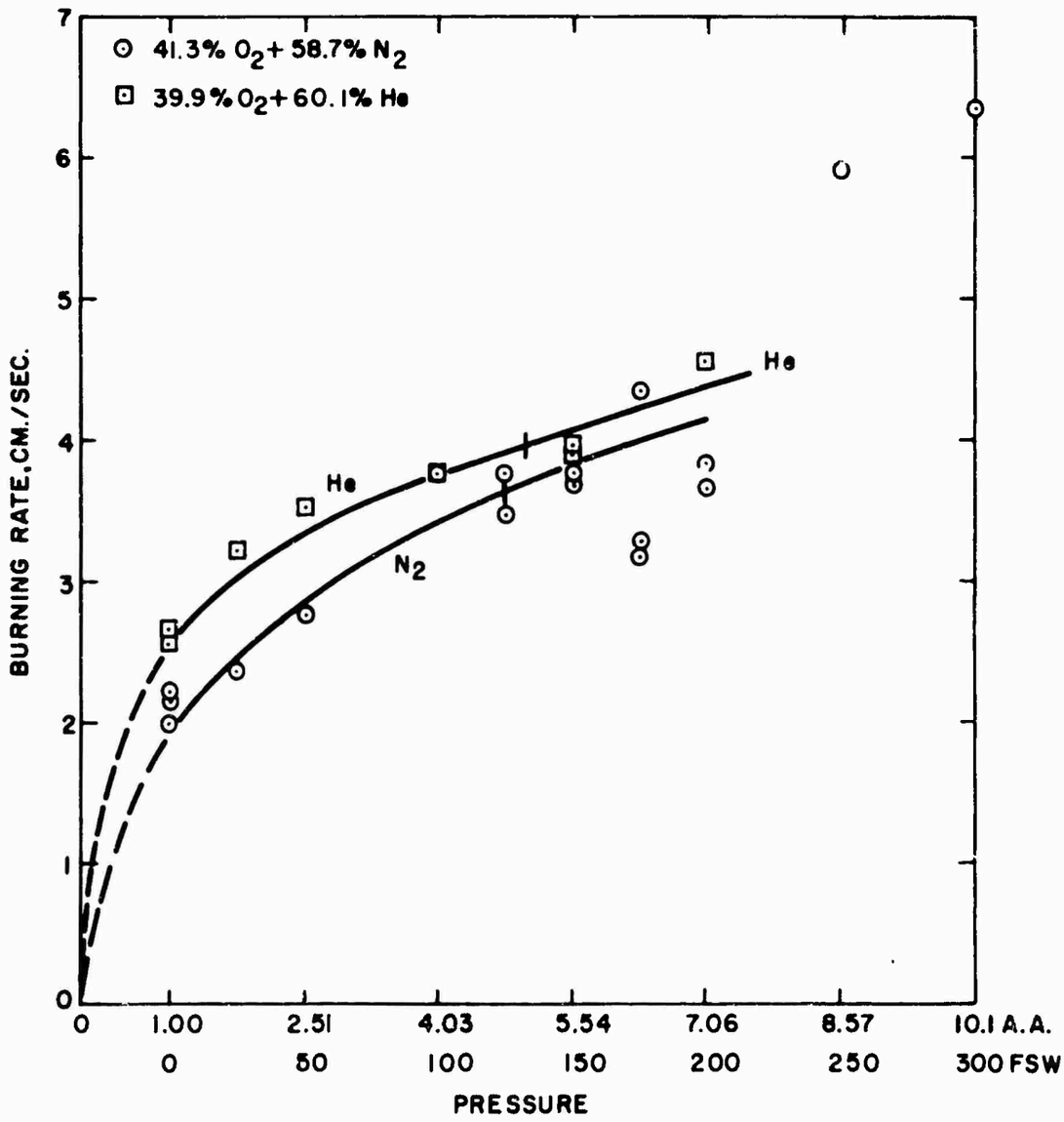


Figure 27. Experimental comparison of helium with nitrogen as oxygen diluents in mixtures containing about 40% oxygen

Fig. 27

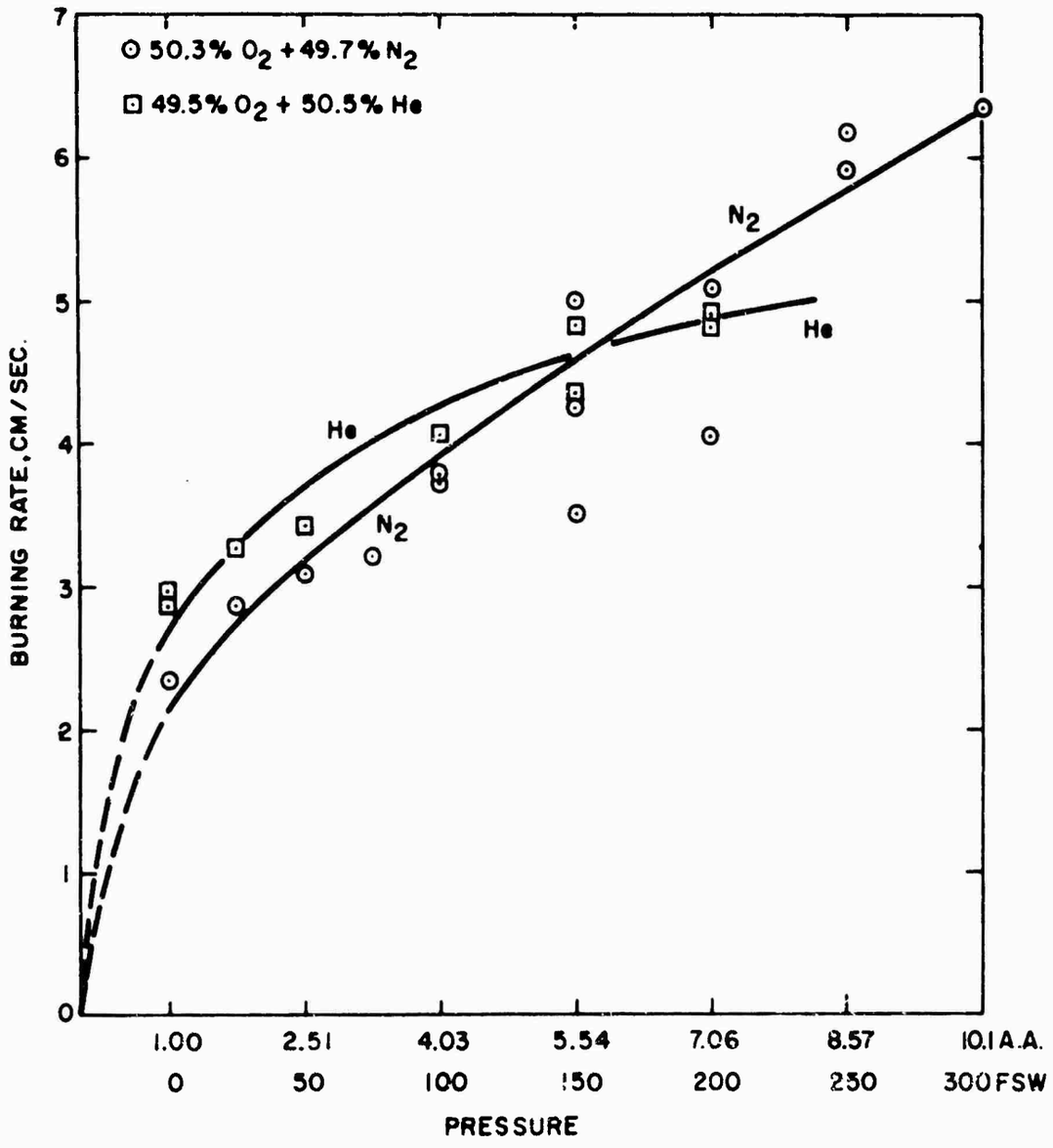


Figure 28. Experimental comparison of helium with nitrogen as oxygen diluents in mixtures containing about 50% oxygen

Fig. 28

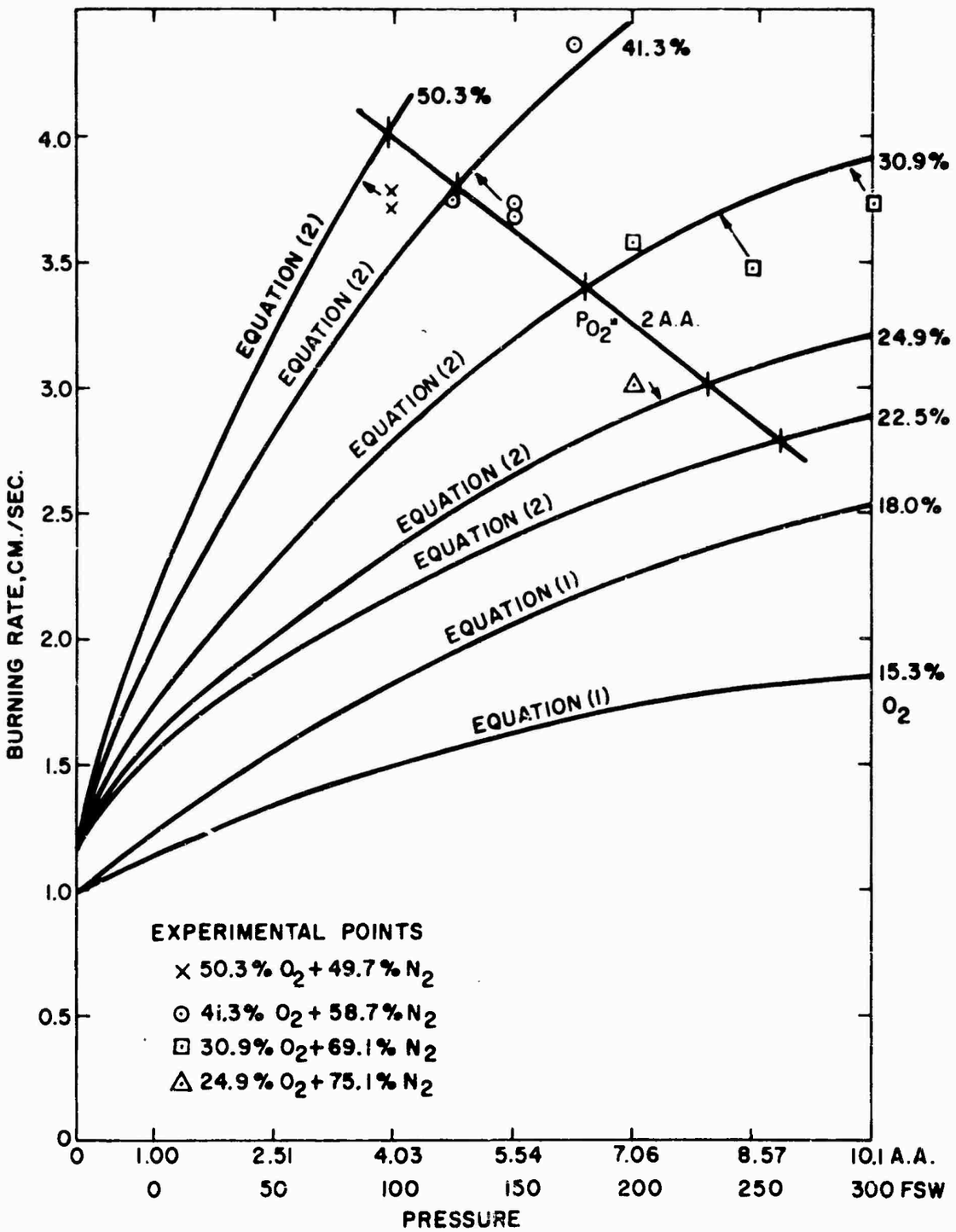


Figure 29. Calculated results for the burning of filter paper strips at an angle of 45° in helium-oxygen mixtures

Fig. 29

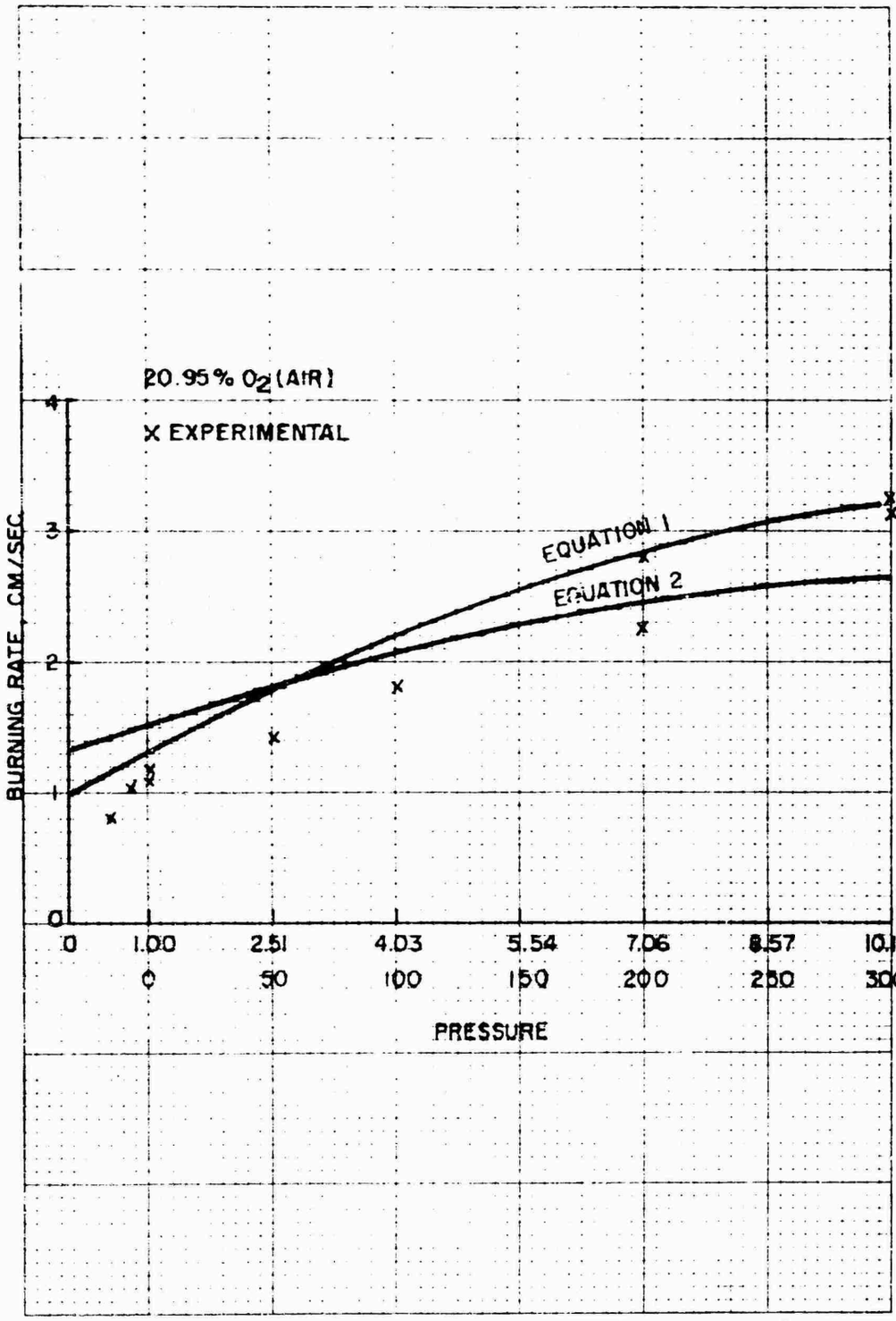


Figure 30. Comparison of calculated with experimental results for air

Fig. 30

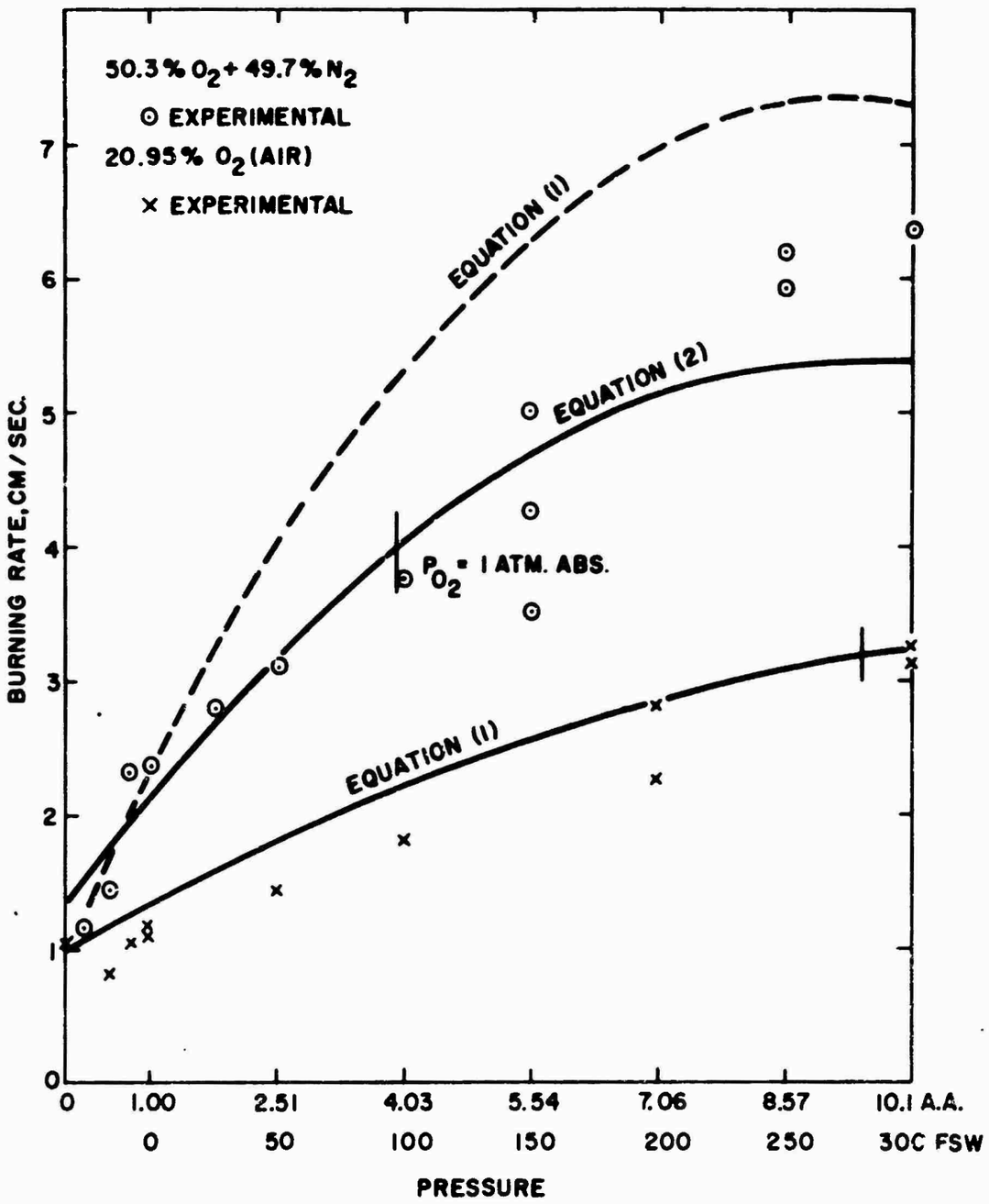


Figure 31. Comparison of calculated with experimental results for air and for a 50% O_2 - 50% N_2 mixture

Fig. 31

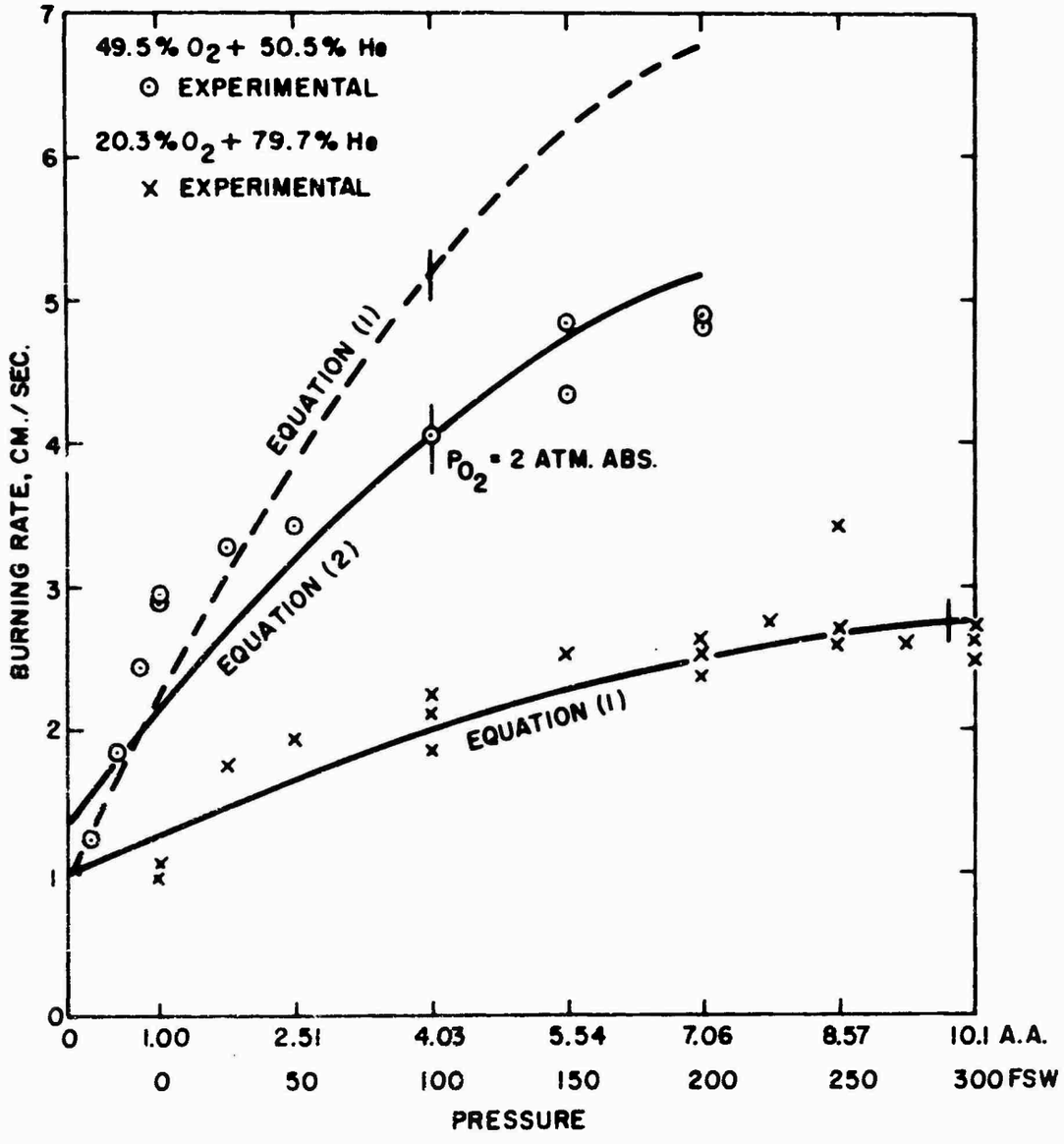


Figure 32. Comparison of calculated with experimental results for helium-oxygen mixtures

Fig. 32

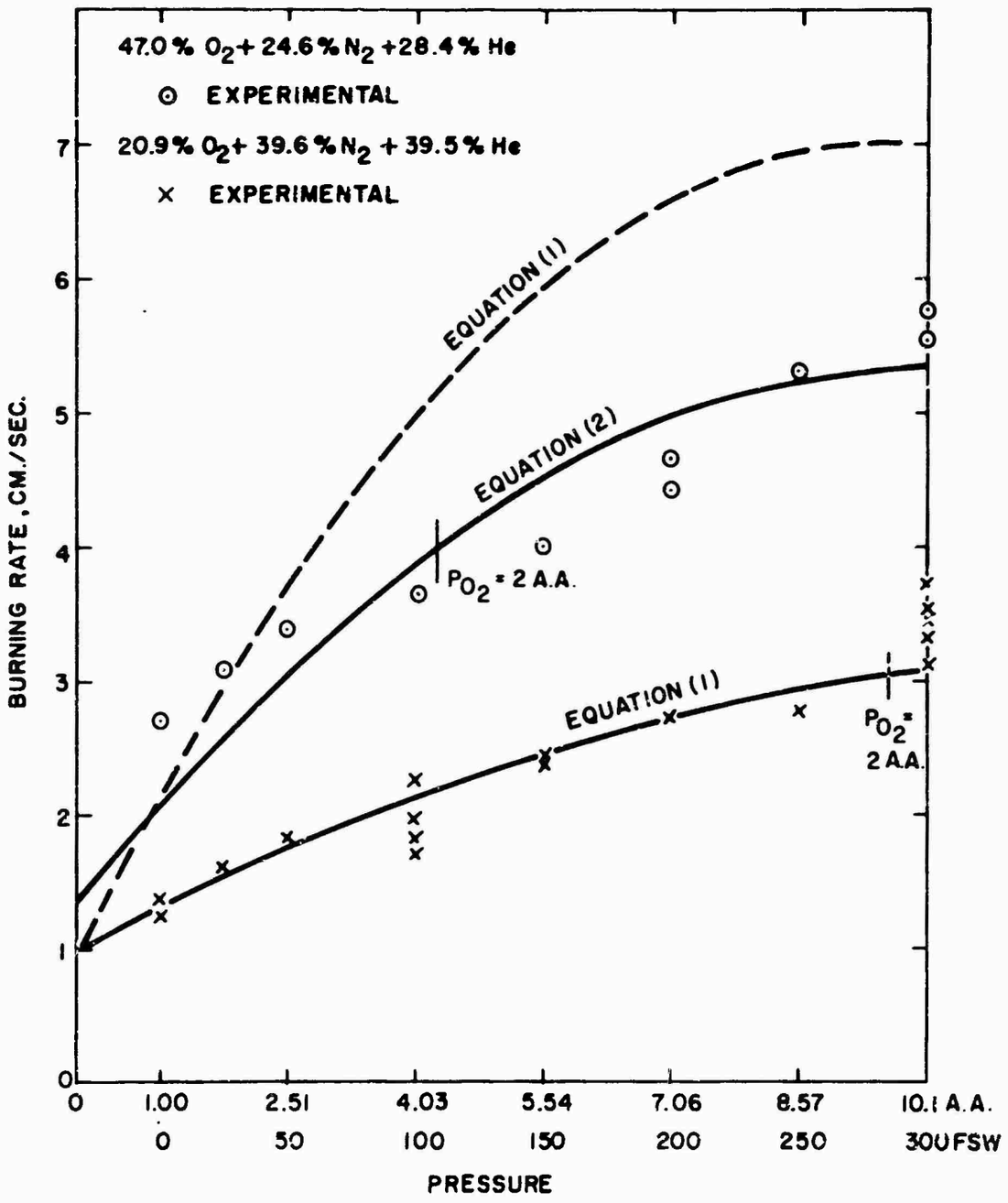


Figure 33. Comparison of calculated with experimental results for nitrogen-helium-oxygen mixtures

Fig. 33

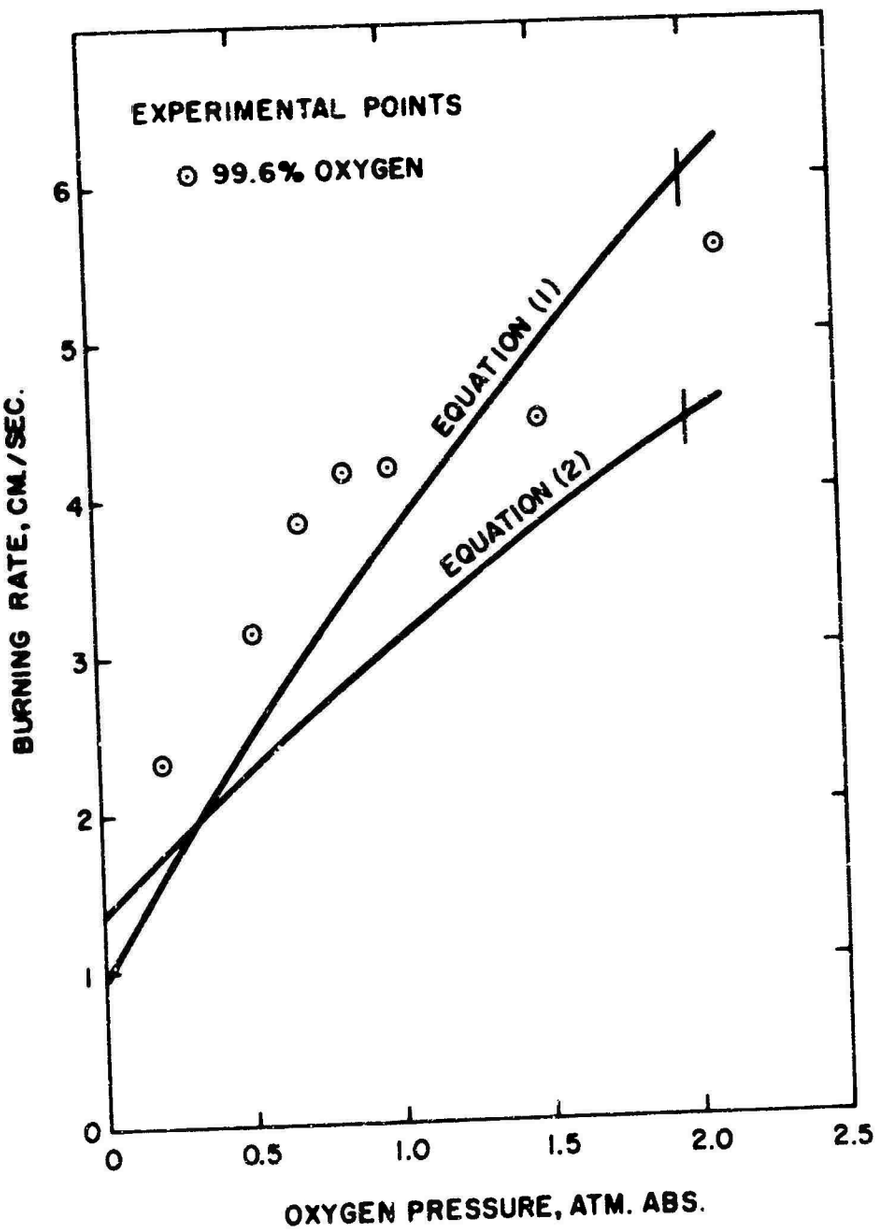


Figure 34. Comparison of calculated with experimental results for 99.6% oxygen

Fig. 34

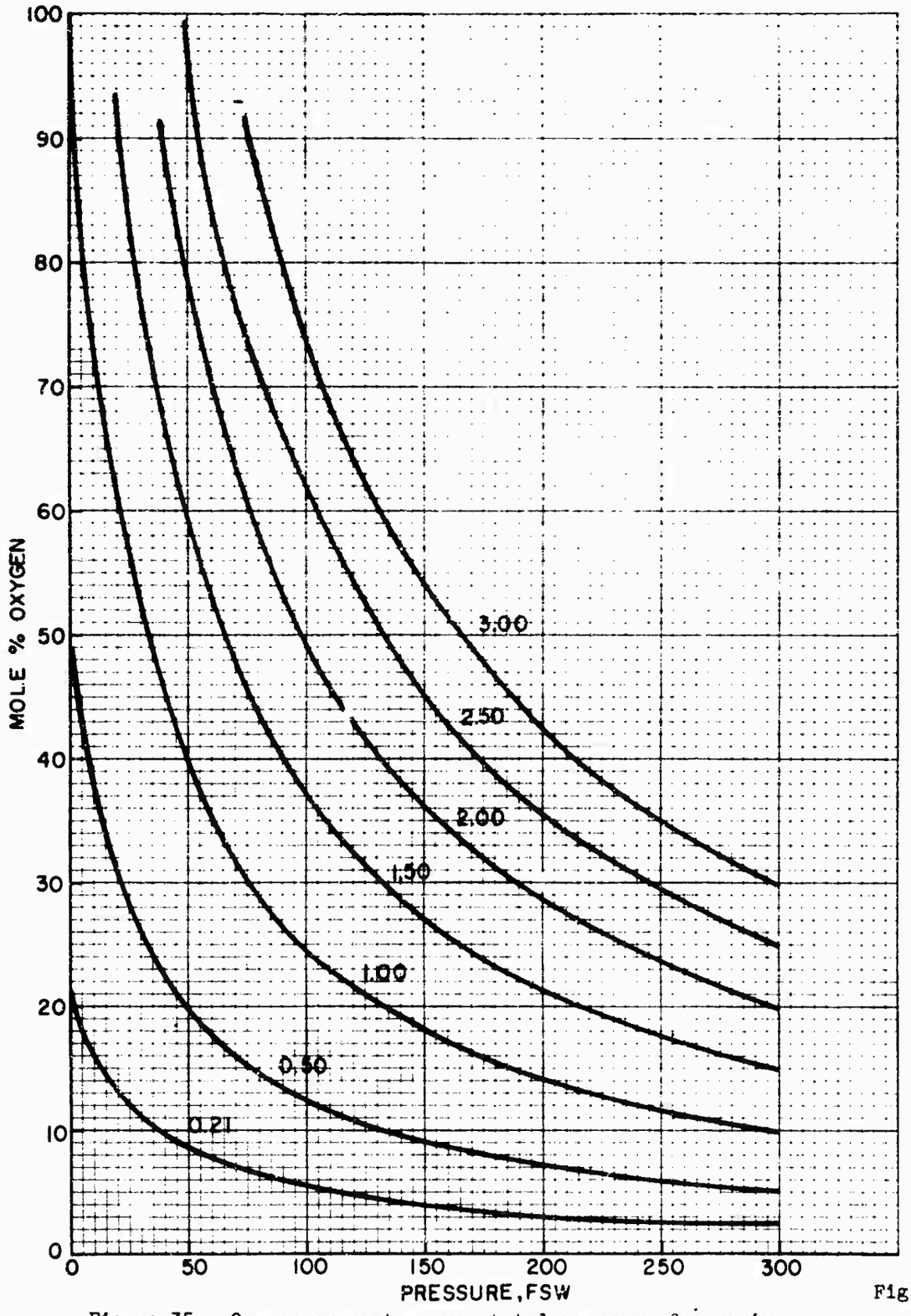


Fig. 35

Figure 35. Oxygen percentage vs. total pressure for various partial pressures (atm. abs.) of oxygen, 0 to 300 fsw

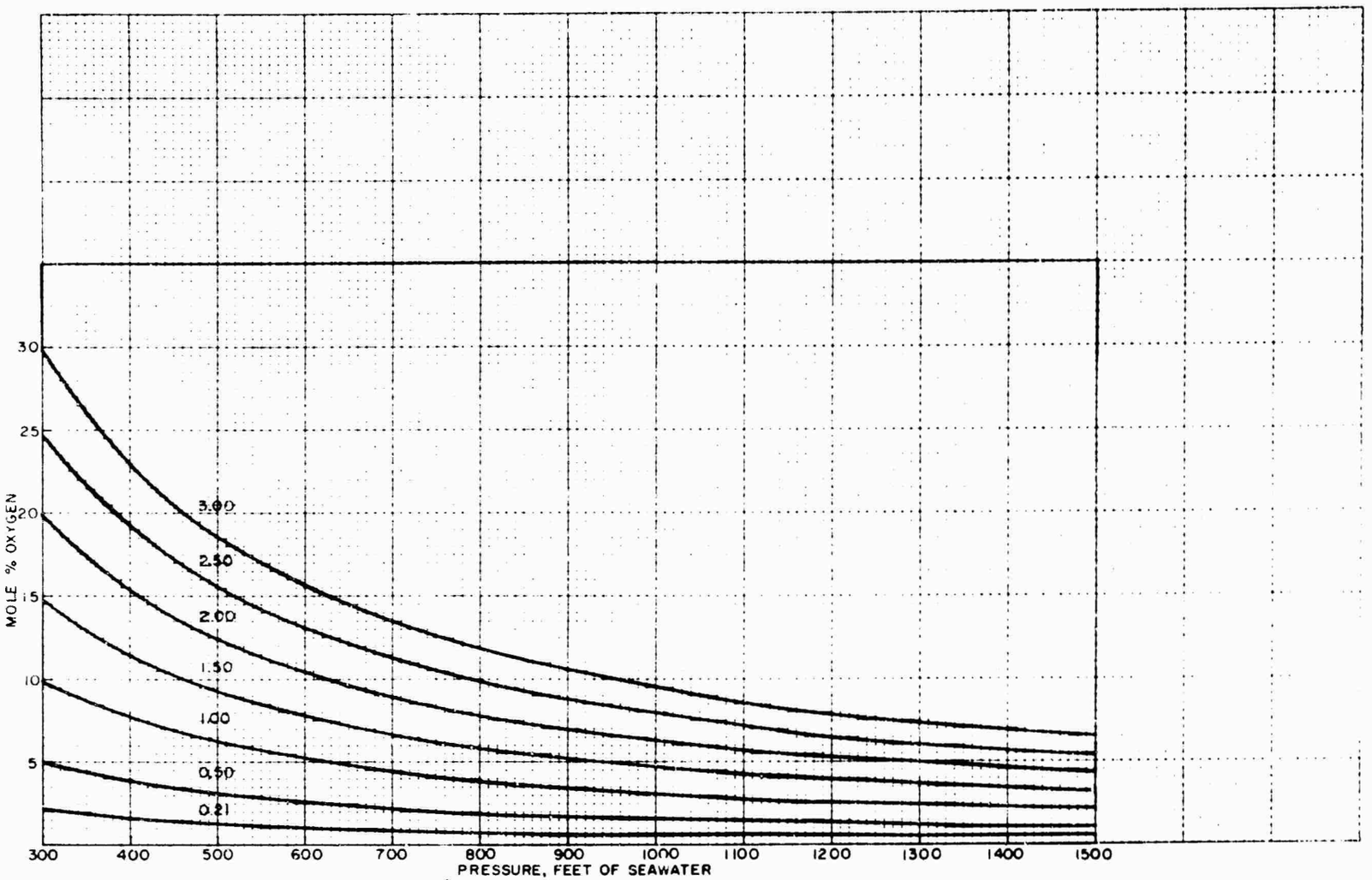


Figure 56. Oxygen percentage vs. total pressure for various partial pressures (atm. abs.) of oxygen, 300 to 1500 fsw

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DOCUMENT CONTROL DATA - R&D

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3 REPORT TITLE SCREENING OF FLAME-RESISTANT MATERIALS AND COMPARISON OF HELIUM WITH NITROGEN FOR USE IN DIVING ATMOSPHERES; FIRST ANNUAL REPORT ON COMBUSTION SAFETY IN DIVING ATMOSPHERES

4 DESCRIPTIVE NOTES (Type of report and inclusive dates)
Annual report covering the period April 1, 1966 - March 31, 1967

5 AUTHOR(S) (Last name, first name, initial)
Cook, Gerhard A., Meierer, Robert E., and Shields, Bruce M.

6 REPORT DATE	7a TOTAL NO OF PAGES	7b NO OF REFS
March 31, 1967	107	62

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N00014-16-C0140 b. PROJECT NO. RR 240-016 c d.	9b OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

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Work on this project is continuing	U.S. Navy, Office of Naval Research and Naval Ship Systems Command

13 ABSTRACT The main purposes of the study carried out during the first year of this contract were: (1) to determine the influence of sample angle, ambient-gas composition (air, oxygen-enriched air, pure oxygen, oxygen-nitrogen mixtures, and oxygen-helium mixtures) and pressure (0 to 1000 feet of seawater) on the burning rate of a typical combustible material, and (2) to procure sample and make a preliminary evaluation, by means of small-scale tests, of fire-resistant or non-combustible textiles, elastomers, insulation, etc. which might be useful in diving-decompression chambers. It is expected that the information developed under this contract will be of value, not only in diving, but also in space-simulation chambers, space vehicles, therapeutic oxygen tents, and the hyperbaric oxygen chambers used in some hospitals.

The experimental results show that under most conditions, everything else being equal, burning takes place more rapidly when helium, rather than nitrogen, is the oxygen diluent.

Samples of over 60 different materials were procured, tested, and tentatively assigned to one of ten classes with respect to fire resistance.

The report also includes a survey of literature published too late to be included in the extensive review by Roth that appeared in 1964.

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Unclassified

Security Classification

14 KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Binding agent						
Cloth, flame-resistant						
Combustion products						
Decomposition, thermosetting resin, fire						
Diffusion, thermosetting resin, fire						
Fabric, flame-resistant						
Fire resistant						
Flame-resistant material						
Flame-resistant material						
Gases, flame, fire						
Hollow, fire						
Nitrogen, fire						
Oxygen, fire						
Safety, fire						
Textile, flame-resistant						

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