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RESEARCH ON IGNITION AND COMBUSTION IN OXYGEN SYSTEMS

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SUMMARY

The work on ignition and combustion research in oxygen systems under the sponsorship of NASA's Aerospace Safety Research and Data Institute (ASRDI) is described. Preliminary results of ignition of nonmetallic materials by electric arc and mechanical impact are presented. Ignition by a resonant process involving repeated shock waves has been demonstrated and some of the results included. In addition, results of studies concerned with ignition due to the rapid rupture of metal films and diaphragms are reviewed.

Burning rate studies of three nonmetallic materials in oxygen enriched environments were completed and the results presented. A brief description of these combustion studies under zero gravity is also included in the paper. These results are compared to combustion under one gravity.

INTRODUCTION

The safety research programs supported by the Aerospace Safety Research and Data Institute at the NASA Lewis Research Center are aimed toward establishing guidelines and specifications for the safe transportation and use of rocket propellants. Although the NASA, using less than 1% of the oxygen manufactured, is not a major user of oxygen in this country, large quantities of oxygen are used in a single application. For example, a Saturn V booster, not counting the upper stages, contains about 1600 tons of liquid oxygen and it is consumed at the rate of about 550 tons per minute after launch.

This paper will present results of studies to evaluate the hazards in oxygen systems and develop safety criteria to aid in the safe design and operation of oxygen flow systems. An overview of the safety research programs is shown in Figure 1.

Literature reviews are performed to obtain information helpful to the planning and operation of the experimental programs. A number of reports have been published summarizing some of these reviews (Refs. 1 - 4). As indicated in Figure 1, two major areas of study are identified: Hazard Evaluation and Safety Criteria. Programs under Hazard Evaluation are those we consider as being directed toward defining safety problems through an understanding of the chemical and physical phenomena involved. Safety Criteria includes measurements of the effects of parameters such as temperature, pressure, and energy thresholds for ignition. Such information is useful for the engineering of a system having an appropriate degree of safety. The modes of ignition under investigation are shown below (Figure 2):

Electric Arc - Short Circuit
Single Impact - Mechanical
Abrasion - Fluid Borne Particles
Resonance Ignition
Fracture - New Metal Surfaces

The intent of the program is to establish ignition thresholds and to define how safety margins can be achieved through the following:

1. Control of dimensions, shape, and location of combustible materials in the system.

2. Limitation of maximum short-circuit current and freedom from ignition by sparks/arcs to combustible materials.

3. Limitation of closure force on valves or other operational devices in oxygen systems to avoid ignition by impact; also to include the effect of load-concentrating grits and combustible contaminants on such limitations.

4. Restrictions on contaminant particle population and flow velocities to avoid ignition by abrasion.

5. Control of possible resonance cavities in oxygen systems which could be exposed to rapidly fluctuating pressure fields generated by unstable systems of shock waves. The temperatures can climb to dangerous levels in the gas near the end of the cavity.

6. Selection of materials with strongly adherent oxide layers. The ignition of some materials appear to be enhanced by exposure of fresh unprotected surfaces.

Programs under the category of Hazard Evaluation include specific combustion research studies such as burning rates of materials and the investigation of zero gravity combustion.

A study of the parameters which control the burning rates of nonmetallic materials is presently under way at the Lewis Research Center. The present apparatus allows experiments over the pressure range of 20 to 1400 psia and the objective is to extend such work to higher ranges of oxygen pressure. With respect to zero gravity combustion, analytical and experimental studies are being performed to determine the effects of gravity on the combustion of gases, burning rates of solids, and on the burning of liquid fuels.

SAFETY CRITERIA IGNITION MODES

Electric Arc

The NASA White Sands Test Facility (WSTF) is presently generating test data by subjecting materials to a constant current electric arc in the presence of high pressure and temperature gaseous oxygen (Ref. 5). A schematic of the apparatus being used at the WSTF to determine threshold arc currents for ignition is shown in Figure 3. Photographs of the ignition test chamber are shown in Figures 4 and 5. The test matrix indicating the variables is shown in Table I. The materials, material thicknesses, pressures, and temperatures to be used should provide an evaluation of typical materials and systems in malfunctions, such as short circuits or damage to electrical insulation. The results should help specify current-limiting devices for the protection of electrical equipment exposed to oxygen.

The preliminary results obtained with Teflon, Viton and Vespel SP-21 are shown in Table II. Data at the minimum and maximum temperatures and pressures are plotted in Figure 6. For Teflon, at the minimum temperature (70°F) and pressure tested (100 psia), as the specimen thickness is increased (0.01 - 0.10 inch), a greater arc current is required to ignite the specimens. With an increase in test temperature to 500°F, the current requirements for the thicker material (0.10 inch) are reduced. At the higher pressure (1000 psia) and at both 70°F and 500°F, the energy required for ignition is the same for both thicknesses of material. The values at the higher pressure were similar to those obtained at the lower pressure (0.01 inch).

With Viton, at the higher pressures, the thickness and test temperature did not affect the arc current requirements for ignition. At the lower pressure, however, the increased thickness at 70°F resulted in a lower current requirement for ignition. In addition, an increase in pressure resulted in increased current requirements for ignition. With Vespel SP-21, no effect of thickness was found with respect to arc current requirements except at 1000 psia and 70°F. At both 100 psia and 1000 psia pressures, an increase in test temperature resulted in an increase in current requirements for ignition. Although a reasonable explanation of the behavior under the various pressures, temperatures and material thicknesses tested is not provided by these tests, the research is continuing.

Impact

Mechanical impact has been recognized as an ignition hazard in oxygen systems and a standard method for screening material has been developed based on this phenomenon (Ref. 6). In this test, a falling weight hits a striker pin resting on the sample.

To extend the significance of the mechanical impact tests to the evaluation of hazards in real systems, a test program as outlined in Table III is presently under way at the NASA WSTF. The variables for the single mechanical impact ignition tests of metals and nonmetals include: energy levels from 100 to 1200 ft. lbs/in^2; sample thicknesses (14-fold range for metals and 100-fold range for nonmetals); relative size of striker and sample (100-fold range); contamination by oil or grits which may act as stress concentrators; pressure ranges from 100 to 5000 psia; and temperature ranges from -250 to 1000°F. In some tests, the threshold energy for impact ignition will be carefully determined, and in others, the effect of presumed sensitizer will be evaluated by go-no-go tests at 75% of the threshold energy for the clean sample.

The apparatus used for these tests is a basic NASA-George C. Marshall Space Flight Center drop weight tester in which the anvil was replaced with a test chamber designed to operate at pressures up to 10,000 psia. In addition, the facility was modified to provide for a single impact. Figure 7 shows a photograph of the impact test system and Figure 8 a schematic of the flow system.

Preliminary results of the single mechanical impact ignition tests are shown in Table IV. Clean Teflon did not react under impact energies up to 1200 ft. lbs/in^2 and pressures up to 5000 psia. Contaminated Teflon, however, depending upon the particular contamination, was found to react at substantially lower pressures and impact energies. Teflon contaminated with Wet Toolmakers Dye reacted at 100 ft. lbs/in^2 impact energy while Teflon contaminated with lubricating oil did not react at 1200 ft. lbs/in^2 impact energy.

Abrasion

Impact of high velocity particles has been recognized as hazardous, especially in gaseous systems, but has received little attention experimentally. Extensive problems exist in equipment design for testing at high pressures and at high flow with known amounts of specific abrasive material. For example, a problem that has not been solved is how to prevent burnout of the complete test apparatus. Table V outlines the program to be carried out at the WSTF. Results of the program should aid in defining particle-impact hazards in quantitative terms. In addition, these studies should certainly affect the specifications for cleaning oxygen systems. A recent survey shows (Ref. 7) different specifications for allowable particle size and number being used by many organizations. An assessment of the particle-impact ignition potential would aid in establishing realistic cleaning requirements.

Resonance Ignition

In typical gas-flow configurations such as the one shown in Figure 9, large temperatures can occur in dead-ends during steady flow. This is caused, not by adiabatic compression, but by a resonant process involving repeated shock waves, as outlined in Figure 10. Temperatures measured in such a system for a flow from a 1000 psia source is shown in Figure 11. Experiments with metal chips in the cavity have produced ignition of the chips followed by burnout of the system. In addition, preliminary results indicate that the metallic samples may be more readily ignited when contaminated with cutting oil. Dead-end configurations are often built into the oxygen flowing system or exist in valves and fittings in which contaminants are apt to collect which may suggest resonance ignition as the initiator of many mishaps.

In addition to the resonance mode of ignition, many oxygen systems produce shock waves that could be the source of the ignition energy required to start the chain of events that leads to catastrophic failure. Conditions leading to failures due to the presence of shock waves is under investigation at the University of Michigan (Prof. J. A. Nicholls). An NASA grant was recently awarded to the university to measure the limits for ignition of metals, lubricants and contaminants by shock waves in oxygen rich environments. Metal spheres and strips of different sizes will be exposed to incident shock waves of various strengths and a range of oxygen concentration and pressure. Lubricants and contaminants will be added to the samples to determine their influence on the ignition limits. A literature survey for pertinent information relating to solid particle ignition has been completed. Consideration is being given to the design of the shock tube, selection of materials, and range of particle size.

Since the nature of interaction between the convective flow and particle should depend upon the ratio of the time for the particles to accelerate (to the convective flow velocity) to the time for the particle to melt, it was decided to initially investigate the situation in which the ratio of the acceleration time to melt time is considerably greater than 1. Under these conditions, it is expected that the particles would liquefy while a large relative convective flow exists and the subsequent behavior is expected in many respects to parallel that of breakup and ignition of liquid fuel drops subjected to shock passage. Using an existing shock tube, calculations performed by Prof. J. A. Nicholls of the acceleration and melting times of homogeneous metal spheres have indicated that zinc particles of the order of 100μ can be used. Also, zinc is readily oxidized by oxygen. A device which injects metal particles into the shock tube is also being designed.

Fracture

The spontaneous ignition of metal films and diaphragms of titanium has occurred upon rapid rupture under various temperatures and pressures. This is most likely caused by the exposure of fresh reactive material, unprotected by an oxide layer. The possibility exists that other metals may also ignite for the same reason and work is being extended to cover materials more likely to be found in oxygen systems.

It is hoped that these studies will shed some light on how normal oxide films inhibit combustion and the conditions under which the protection fails. The apparatus shown in Figure 12 is being used at the Lewis Research Center to investigate the reactions of several metals when fractured in an oxygen environment. A pneumatically-driven plunger ruptures a metal foil inside a chamber in which the tests may be performed at elevated temperatures and pressures. The results so far are summarized in Table VI. Only titanium has been found to ignite in these tests, and it does so at room temperature and at all pressures of pure oxygen above 65 psia as shown in Figure 13. Tests at temperatures up to 1000°F have not shown any appreciable reduction in this pressure limit. On the other hand, dilution of oxygen with nitrogen greatly increases the pressure required for fracture-ignition of titanium foils. Figure 14 shows this effect for room temperature tests.

Ignition of metal foils other than those made of titanium has not been observed. Aluminum has withstood this test at 1400 psia. The results, however, may be different when these apparently safe metals are tested at still higher temperatures and pressures. Also, results with alloys may be different from those of the pure metals that have been tested.

HAZARD EVALUATION

Burning Rate Studies

Experiments were performed to measure flame spreading and mass consumption rates for nylon, polymethylmethacrylate and Teflon surfaces in enriched environments. These studies extended the work of that presented in References 8 and 9 to higher pressures (up to 80 atm.) and to a different geometry. The samples were cylindrical and were burned at various pressures in environments ranging from pure oxygen to 20% oxygen - 80% nitrogen with an average free stream velocity of from 0 to 8 meters per second.

The apparatus used is shown in Figure 15. The test specimen is mounted along the centerline of the test chamber and is ignited at the top with a nichrome wire igniter and burns downward. In this configuration, the flame must advance against the flow of oxygen. The effect of oxygen pressure on the flame spread rate for Teflon is shown in Figure 16. The data are presented for two gas velocities. For Teflon, the flame spread rate is proportional to pressure to the 1.10 power; for nylon and polymethylmethacrylate, the rate is proportional to the 0.75 power. These correlations agree quite well with those presented in Reference 5. Tests on the effect of oxygen concentration showed an increase in flame spread rate with concentrations. Also, results showed that in 50% O_2/N_2 mixture, Teflon would not burn at pressures up to 2000 psia. The effects of oxygen flow on flame spread rates were obtained for the three materials. In an NASA report on this work, to be published soon by J. J. Notardonato, L. A. Burkardt and T. H. Cochran (Ref. 10), an effort is made to define three distinct regions as the gas velocity past the flame front increases. Initially, as the gas velocity is increased, the flame spread rate increases - Region I; continued increases in gas velocity then caused a reduction in the flame spread rate - Region II; followed by an increase in the flame spread rate (Region III) at the highest velocities studied.

Figure 17, which is for Teflon, shows Regions II and III. Figure 18 shows Regions I and II for polymethylmethacrylate. It is suggested that the increase in flame spread rate in Region I is probably due to the increased availability of oxygen to the reaction zone from convective mass transfer effects. In Region II, the increased heat transfer away from the reaction zone due to increased convection and the tendency to sweep the reactants downstream become the major effect and the flame spread begins to decrease. In Region III, with increased gas velocity, it is postulated that the reaction zone boundary probably moves inside the flow boundary layer making oxygen availability the dominating factor. The data show that the pressure (P), gas velocity (V_g) and concentration have the following effect on flame spread rates:

1. At low gas velocities (Region I)

   $V = KP^{0.75} Y_{ox}^{1.5} V_g^{3.3}$ - for nylon and polymethylmethacrylate

   $V = KP^{1.1} Y_{ox}^{4.4} V_g^{0.33}$ - for Teflon

2. At medium gas velocities (Region II)

   $V = KP^{0.75} Y_{ox}^{1.5} V_g^{0.5}$ - for nylon and polymethylmethacrylate

   $V = KP^{1.1} Y_{ox}^{4.4} V_g^{0.5}$ - for Teflon

3. At highest gas velocities studies (Region III) - effects on velocity on flame spread rate were complex.

Zero Gravity Combustion

Combustion under zero gravity continues to be a concern because of the possibility of fires aboard spacecraft and because of the need for the development of methods of controlling them. Recent efforts at the Lewis Research Center have included the study of the burning of laminar gas jet diffusion flames in a zero gravity environment (Refs. 11 & 12). The Lewis Research Center has available two drop towers which provide for 2.2 and 5.2 seconds of zero gravity. The fuels used for the diffusion flame studies included hydrogen, methane, ethylene, and propylene. The studies showed that the burning characteristics under zero gravity are different than under normal gravity but demonstrated the existence of steady state flames under zero gravity. The geometry and stability of the flames are different under zero gravity; methane-air flames were approximately 50% longer and wider in zero gravity than in normal gravity.

The behavior of the flame in zero gravity was found to be a function of the burner size and gas-jet Reynolds number. Flame length correlations for the fuels were validated by comparison with the data obtained.

A study is also under way on the effects of gravity on the burning rates of various materials, including metals, in a supercritical oxygen atmosphere. Results have been obtained with Teflon insulated wires, stainless steel, aluminum, titanium, and inconel. Teflon and cellulose acetate plastics have also been tested to obtain a comparison of burning in normal and zero gravity.

Results have shown that Teflon insulated wires will burn in weightlessness with a self-propagating flame (Ref. 13). The flame spread rate appears to be lower under zero gravity than in normal gravity.

Tests with the metals have shown that once ignited, the material will continue to burn in supercritical oxygen (920 psia, -180°F). Results with inconel showed melting during burning. Tests have also been performed to determine the effect of inert gases on the combustion of solids in weightlessness. The flame spread rate of cellulose acetate in thicknesses of 0.001 and 0.002 inch was obtained in oxygen and oxygen-inert gas mixtures containing from 100 to 60 percent by volume of oxygen. Mixtures of oxygen and helium, argon and nitrogen were used. Adding an inert gas to oxygen reduces the flame spread rate in both zero gravity and normal gravity. Helium gas appears to be less effective than argon or nitrogen in retarding the burning rate in 0-G and 1-G. Tests with various thicknesses of material indicated the flame spread rate is inversely proportioned to the material thickness in both 0-G and 1-G. Experimentation on the effects of lean oxygen concentrations, less than 50%, on the burning rates of cellulosic materials in zero gravity is about to be initiated in the 500-foot drop tower facility.

CONCLUDING REMARKS

The intention of this review has been to identify and describe some of the progress being made in the ignition and combustion studies under the sponsorship of NASA's Aerospace Safety Research and Data Institute.

Results of some related programs under way at other NASA Centers were also presented and they should contribute to the safe design and operation of oxygen systems. Much more work is needed to define the selection criteria especially for use in the high pressure range.

For an accident situation, ignition is almost always assumed and the propagation of burning is what determines the nature of the accident. The role of contaminants is important for ignition and the studies initiated under ASRDI should be expanded. Other areas of research which should be explored include effects of oxygen on the physical and chemical quality of materials, oxide film formation as a function of temperature and pressure, alteration of mechanical properties in an oxygen environment (fracture mechanics), stress corrosion and surface effects, and, particularly for high pressures, ignition and combustion theory.

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TABLE I. - IGNITION BY ELECTRIC ARC

DETERMINATION OF ENERGY THRESHOLDS[a]

MATERIAL	THICKNESS, IN.			PRESSURE, PSIA			TEMPERATURE, °F		
METALLICS	0.01	0.070	0.140	100	1000	5000	-250	70	1000
STAINLESS STEEL	X	X	X	X	X	X	X	X	X
MONEL	X				X				
PHOSPHOR BRONZE	X				X				
NONMETALLICS	0.001	0.01	0.10	100	1000	5000	-250	70	b
TEFLON	X	X	X	X	X	X	X	X	X
VITON			X		X			X	
HIGH TEMP INSULATION		X			X				X

[a]ARC - 0.1-20.0 AMPS; DURATION UP TO 2 SEC.
[b]MAX TEMP - 500° F OR USE TEMP + 50%.

CS-65842

TABLE II. - IGNITION BY ELECTRIC ARC - TEFLON

(PRELIMINARY DATA)

THICKNESS, IN. / ARC CURRENT, MA	0.003		0.01		0.10	
	NO. IGNITIONS / NO. TESTS	BURN TIME, SEC	NO. IGNITIONS / NO. TESTS	BURN TIME, SEC	NO. IGNITIONS / NO. TESTS	BURN TIME, SEC
PRESSURE = 100 PSIA; TEMPERATURE = 70^0 F						
100	0/4	0				
150	1/5	1.2	0/4	0		
200	1/2	2.0	5/5	2.7		
250	5/6	2.0			0/2	0
300					1/2	12.0
350					4/4	11.8
PRESSURE = 100 PSIA; TEMPERATURE = 500^0 F						
50					0/4	0
100			0/4	0	4/4	11.5
150	0/4	0	2/6	2.8		
200	4/4	1.0	1/5	3.0		
250			4/4	2.1		
PRESSURE = 1000 PSIA; TEMPERATURE = 70^0 F						
150	0/4	0	0/4	0	0/4	0
200	4/4	0.5	4/4	1.8	4/4	8.1
PRESSURE = 1000 PSIA; TEMPERATURE = 500^0 F						
150	0/4	0	0/4	0	0/4	0
200	4/4	1.0	5/5	1.1	5/5	6.5

TABLE II. - CONTINUED. IGNITION BY ELECTRIC ARC. VESPEL SP-21
(PRELIMINARY DATA)

THICKNESS, IN. / ARC CURRENT, MA	0.01		0.07		0.10	
	NO. IGNITIONS / NO. TESTS	BURN TIME, SEC	NO. IGNITIONS / NO. TESTS	BURN TIME, SEC	NO. IGNITIONS / NO. TESTS	BURN TIME, SEC
PRESSURE = 100 PSIA; TEMPERATURE = 70^0 F						
50	0/4	0			0/4	0
100	5/5	6.0	0/4	0	5/5	17.0
150			5/5	14.1		
PRESSURE = 100 PSIA; TEMPERATURE = 500^0 F						
100	0/4	0	0/4	0	0/4	0
150	5/5	3.6	5/5	12.0	5/5	15.0
PRESSURE = 1000 PSIA; TEMPERATURE = 70^0 F						
100	0/4	0				
150	4/4	3.2	0/4	0	0/4	0
200			5/5	9.8	5/5	12.0
PRESSURE = 1000 PSIA; TEMPERATURE = 500^0 F						
200	0/5	0	0/4	0	0/4	0
250	5/5	4.0	5/5	10.0	5/5	9.0

TABLE II. - CONCLUDED. IGNITION BY ELECTRIC ARC - VITON
(PRELIMINARY DATA)

THICKNESS, IN. / ARC CURRENT, MA	0.01		0.07		0.10	
	NO. IGNITIONS / NO. TESTS	BURN TIME, SEC	NO. IGNITIONS / NO. TESTS	BURN TIME, SEC	NO. IGNITIONS / NO. TESTS	BURN TIME, SEC
PRESSURE = 100 PSIA; TEMPERATURE = 70^{0} F						
50	0/4	0			0/4	0
100	1/2	5.1	0/4	0	5/5	16.0
150	5/5	5.4	5/5	12.0		
PRESSURE = 100 PSIA; TEMPERATURE = 500^{0} F						
50	0/4	0	0/5	0	3/7	14.2
100	5/5	4.0	5/5	11.1	1/1	14.5
150					1/1	14.2
PRESSURE = 1000 PSIA; TEMPERATURE = 70^{0} F						
50			0/5	0		
100			5/5	10.5		
150	0/4	0			0/4	0
200	5/5	3.1			5/5	12.2
PRESSURE = 1000 PSIA; TEMPERATURE = 500^{0} F						
150	0/5	0	0/4	0	0/5	0
200	5/5	3.0	5/5	11.0	5/5	14.0

TABLE III. - IGNITION BY MECHANICAL IMPACT[a]

DETERMINATION OF ENERGY THRESHOLDS

MATERIAL	THICKNESS, IN.			STRIKER PIN-SAMPLE BEARING AREA			PRESSURE, PSIA			TEMPERATURE, °F		
METALLICS	0.01	0.07	0.140	$0.1a^2$	$1a^2$	$10a^2$	100	1000	5000	-250	70	1000
STAINLESS STEEL	X	X	X	X	X	X	X	X	X	X	X	X
STAINLESS STEEL W/NONIGNITIBLE GRIT	X			X	X	X		X			X	
STAINLESS STEEL W/CUTTING OIL FILM	X			X	X	X		X			X	
STAINLESS STEEL W/LUBRICATING OIL FILM[b]	X				X			X			X	
NOTE[c]												
NONMETALLICS	0.001	0.01	0.10	$0.1a^2$	$1a^2$	$10a^2$	100	1000	500	-250	70	1000
TEFLON	X	X	X	X	X	X	X	X	X	X	X	X
TEFLON W/NONIGNITIBLE GRIT		X		X	X	X		X			X	
TEFLON W/CUTTING OIL FILM[b]		X			X			X			X	

[a]ENERGY LEVELS - 100 TO 1200 FT-LB/IN.^{2}

[b]SIMILAR TESTS TO BE PERFORMED USING OTHER CONTAMINANTS.

[c]SIMILAR SERIES OF TESTS WITH ALUMINUM.

CS-65848

TABLE IV. - SINGLE MECHANICAL IMPACT IGNITION

PRELIMINARY DATA

CLEAN TEFLON				
DIAMETER, IN.	THICKNESS, IN.	PRESSURE, PSIA	IMPACT ENERGY, FT-LB/IN.^{2}	RESULTS
0.100	0.010	100	1200	NO REACTION
0.250	0.003	100	300	NO REACTION
.250	.010	100, 5000	1200	NO REACTION
.250	.100	100	300	NO REACTION
0.500	0.010	1000	1200	NO REACTION

CS-66369

TABLE IV. - CONCLUDED. SINGLE MECHANICAL IMPACT IGNITION PRELIMINARY DATA

DIAMETER, IN.	THICKNESS, IN.	PRESSURE, PSIA	IMPACT ENERGY, FT-LB/IN.^{2}	RESULTS
TEFLON CONTAMINATED WITH CUTTING OIL FILM				
0.100	0.010	1000	→ 1200	NO REACTION
.250	.010	1000	→ 900	REACTION ABOVE 400 FT-LB/IN.^{2}
.250	.100	1000	→ 1200	NO REACTION
TEFLON CONTAMINATED WITH LUBRICATING OIL FILM				
0.250	0.010	1000	→ 1200	NO REACTION
TEFLON CONTAMINATED WITH WET TOOLMAKER'S DYE FILM				
0.250	0.010	1000	→ 1200	REACTION ABOVE 100 FT-LB/IN.^{2}
TEFLON CONTAMINATED WITH 60 μM SILICON DIOXIDE GRIT				
0.250	0.010	1000	→ 1200	REACTION ABOVE 500 FT-LB/IN.^{2}
TEFLON CONTAMINATED WITH 60 μM COPPER GRIT				
0.250	0.010	1000	→ 1200	NO REACTION

CS-66376

TABLE V. - IGNITION BY PARTICLE IMPACT (ABRASIVES)

DETERMINATION OF ENERGY THRESHOLD

METALS -

STAINLESS STEEL, ALUMINUM, MONEL, INCONEL, PHOSPHOR BRONZE, BRASS

NONMETALS -

TEFLON, VITON, VESPEL SP-21

THICKNESS (IN.) -

0.1, 0.5, 1.0

DIAMETER (IN.) -

0.5 & 2 TIMES ABRASIVE JET DIAM

VELOCITY, FT/SEC -

100, 300, 500, 1000

PRESSURE (PSIA) -

100, 1000, 5000

ABRASIVES -

SAND, WELD SCALE (SIZES - 0.001 & 0.0001 IN.)

CS-65841

TABLE VI. - METALS TESTED IN 100 PERCENT OXYGEN

METAL	TEMP, ^{0}F	PRESSURE, PSI	IGNITION	REMARKS
ALUMINUM	80	1000	NO	
ALUMINUM	80	1400	NO	
COLUMBIUM	80	UP TO 900	NO	
TANTALUM	80	UP TO 900	NO	
TITANIUM	80	65	YES	TOTAL OF 47 RUNS WERE MADE
STAINLESS STEEL - 304	80	UP TO 900	NO	
VANADIUM	80	383	NO	
ZIRCONIUM	80	70-90	NO	

CS-65843

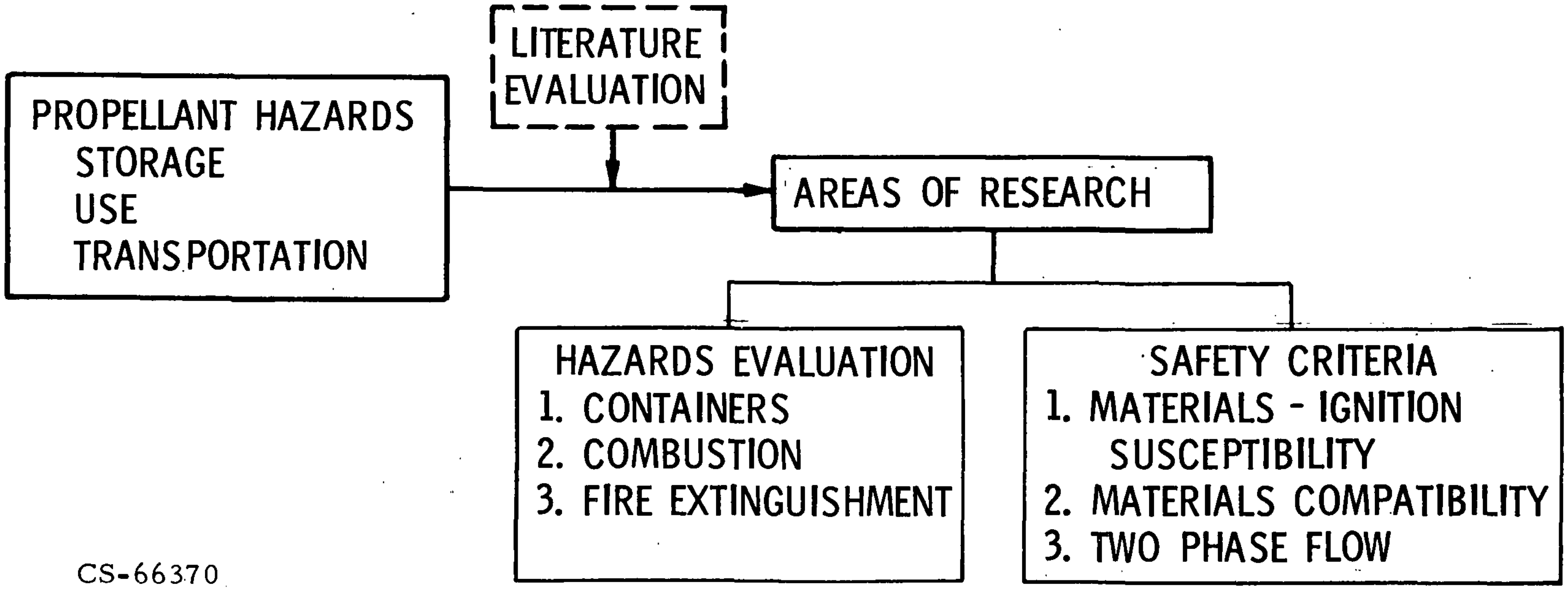


Figure 1. - Safety research programs.

PROPELLANT HAZARDS RESEARCH

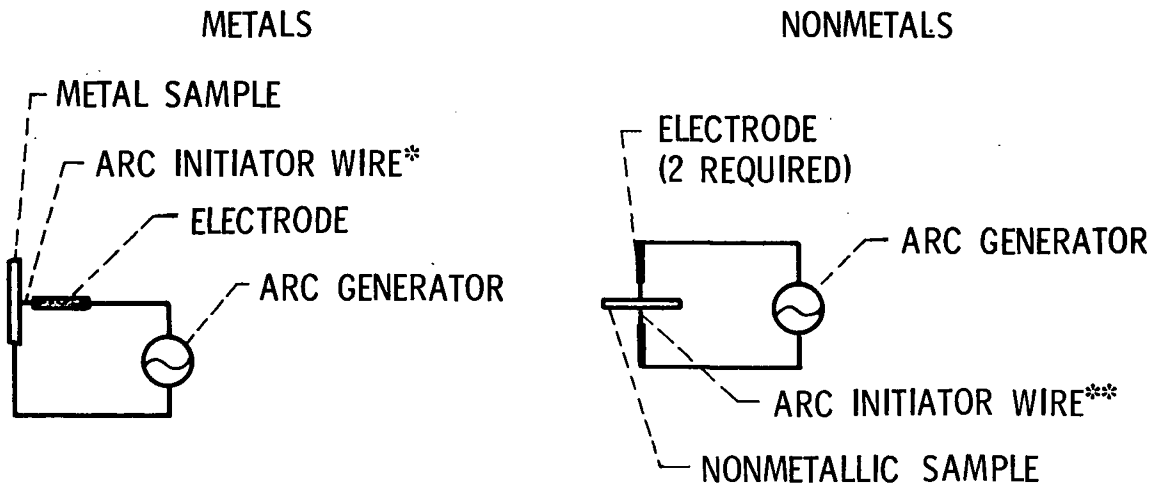
SAFETY CRITERIA

MATERIALS - IGNITION SUSCEPTIBILITY

1. ELECTRIC ARC - (SHORT CIRCUIT, LIGHTNING)
2. MECHANICAL IMPACT - (PARTICLES, VALVE CLOSURES)
3. PARTICLE IMPACT - (RUST, SCALE)
4. RESONANCE TUBE - (HAZARDOUS PIPING CONFIGURATION)
5. FRACTURE - (NEW METAL SURFACE)

Figure 2. - Modes of ignition.

IGNITION BY ELECTRIC ARC



*SHORT CIRCUIT CURRENT DETERMINED BY ARC INITIATOR WIRE DIAM.
**SHOULD ARC INITIATOR CONCEPT BE UNSUCCESSFUL, A HIGH VOLTAGE SPARK WILL BE USED TO INITIATE THE ARC.

VARIABLES INCLUDE

- TEMPERATURE - -250, 70° F, 1000° F
- PRESSURE - 100, 1000, 5000 PSI
- CURRENT - 20.5, 0.5 AMPS
- MATERIAL THICKNESSES
- MATERIALS - S.S., MONEL, BRONZE, TEFLON, VITON

CS-65844

Figure 3.

E-7419

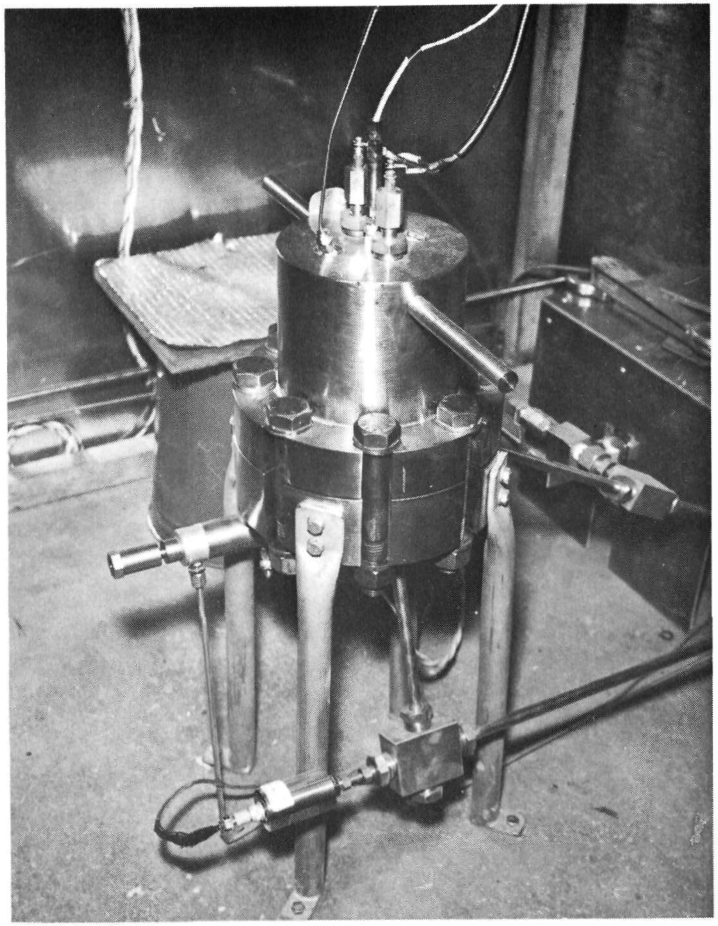


Figure 4. - Electrical arc ignition test chamber (assembled).

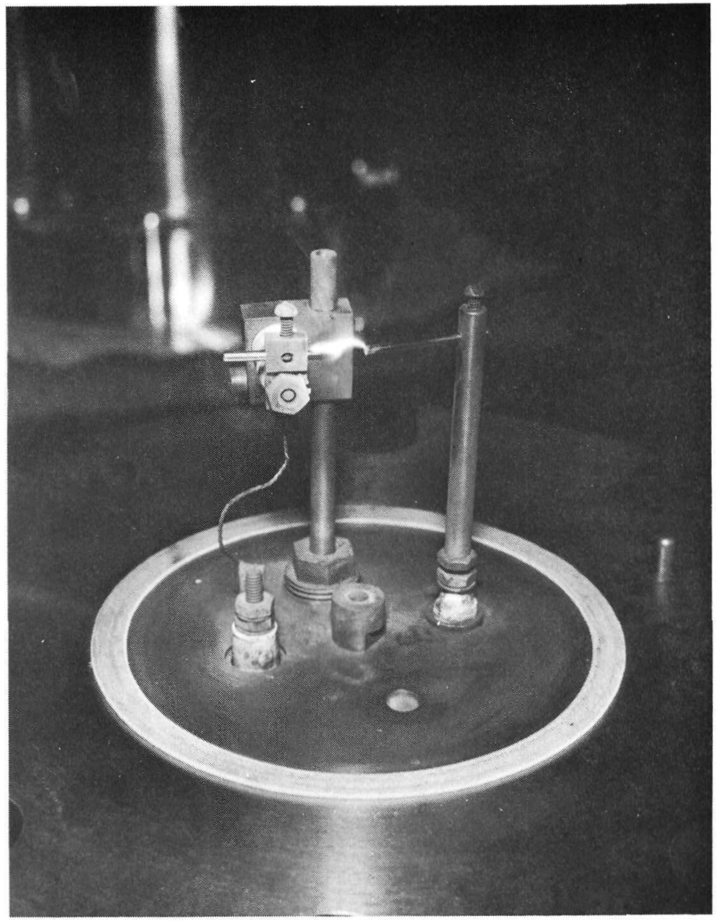
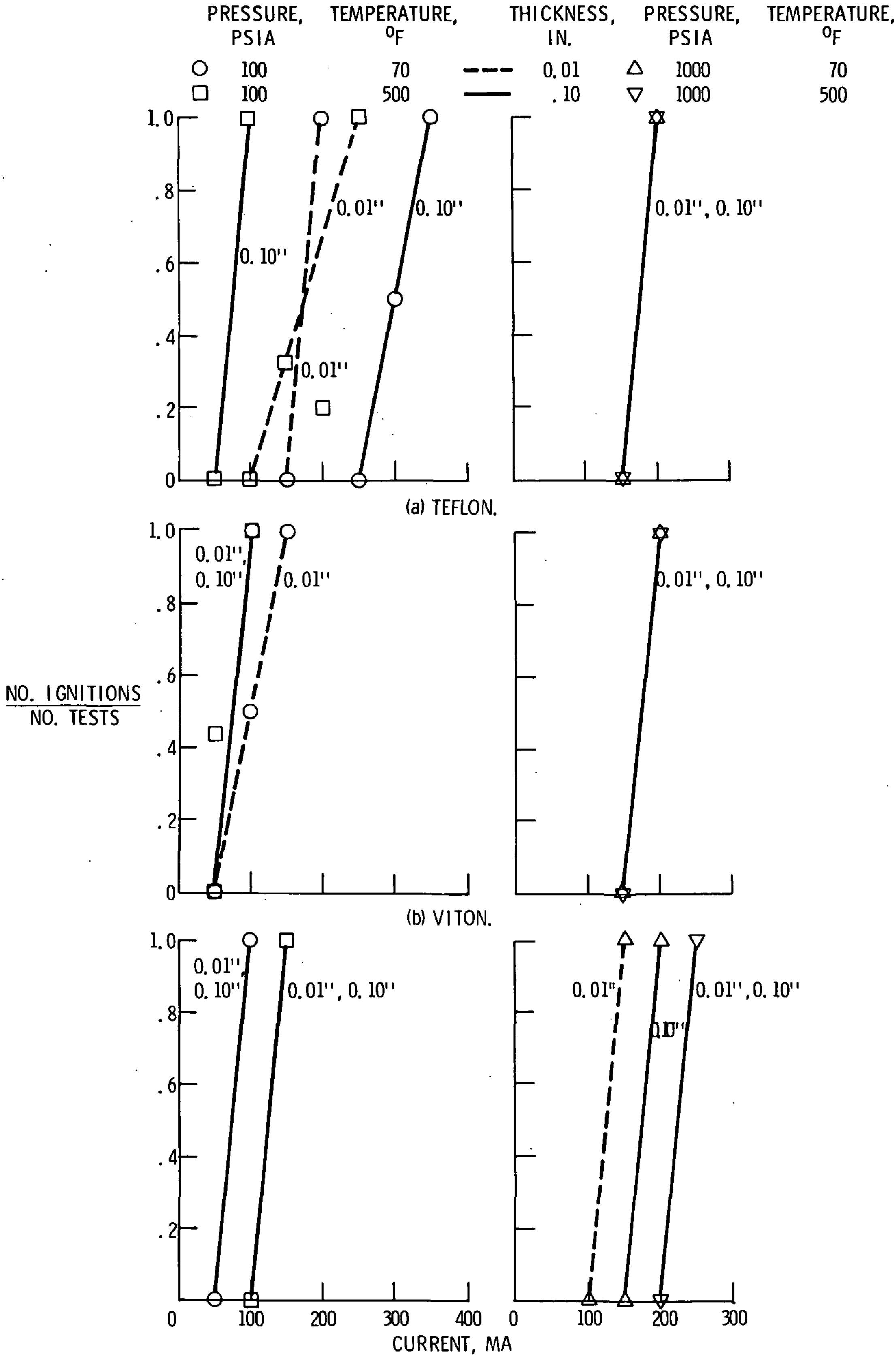


Figure 5. - Electrical arc ignition test chamber (arc depiction).



(c) VESPEL SP-21.

Figure 6. - Ignition by electric arc.

E-7419

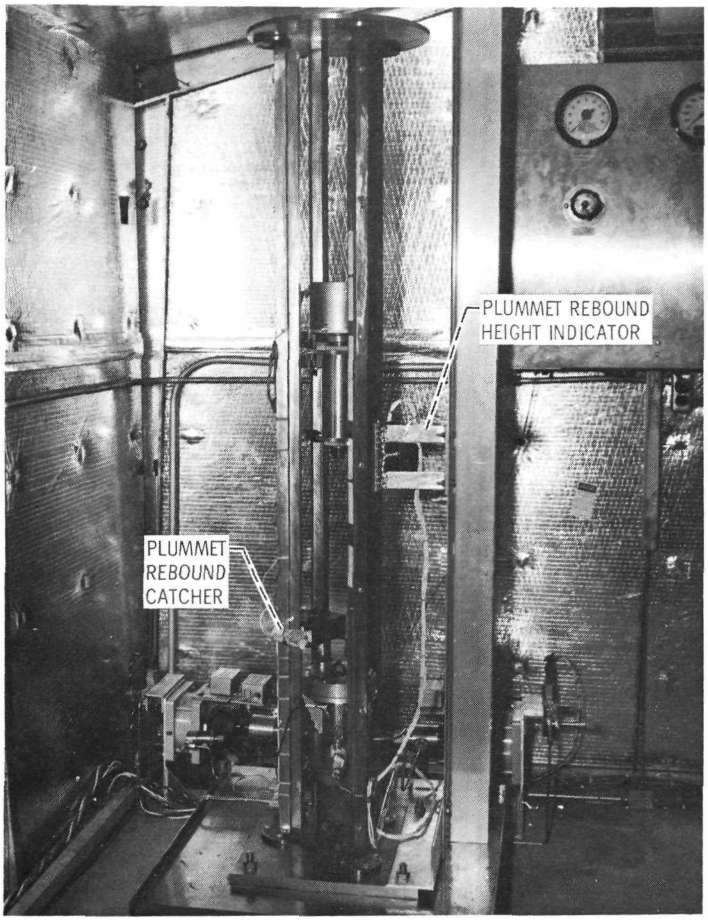


Figure 7. - Single mechanical impact test system.

WSTF MECHANICAL IMPACT TEST SYSTEM

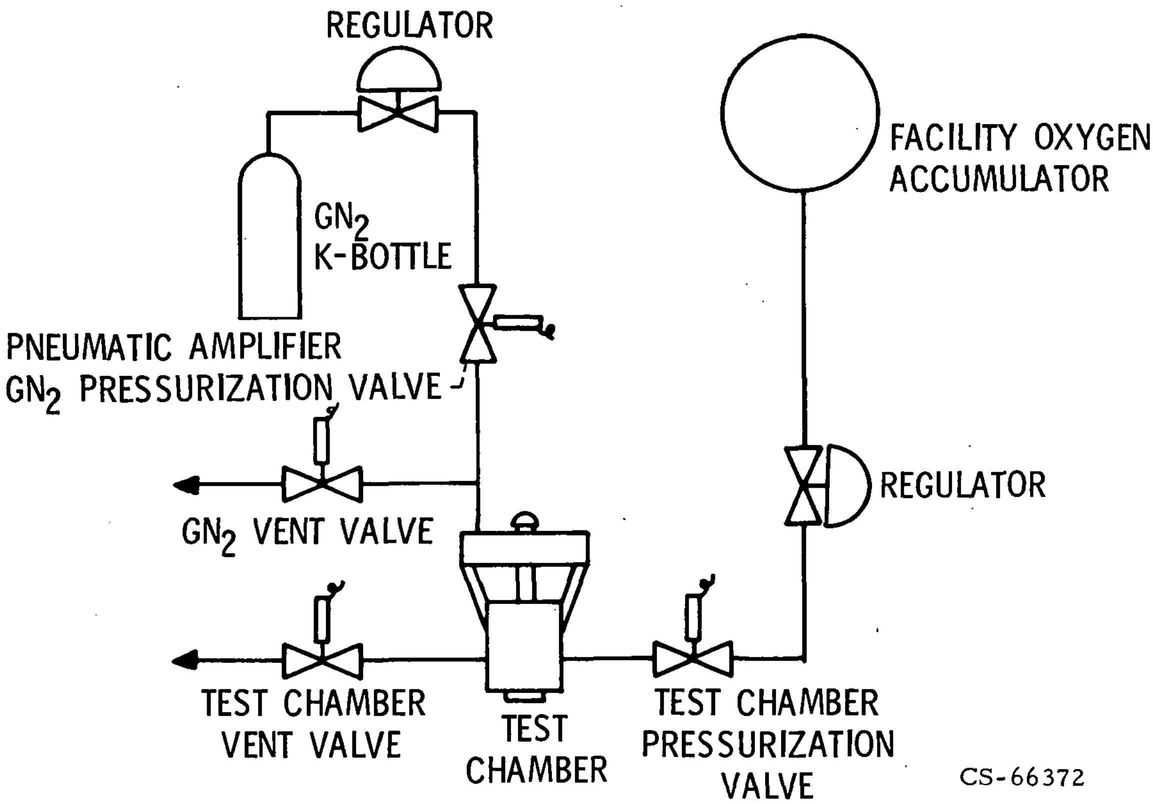
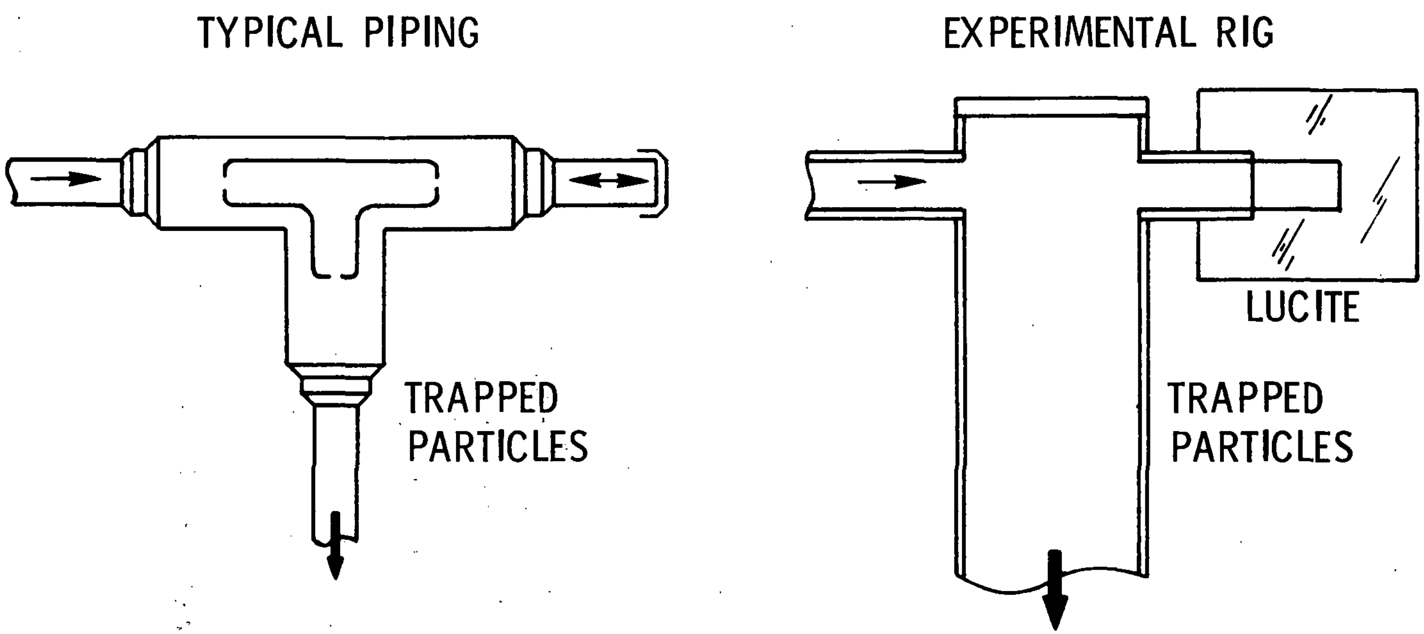


Figure 8.

IGNITION IN RESONANT CAVITIES[a]



[a]VARIABLES INCLUDE TUBE SIZE, PRESSURE, METALS, & NONMETALS.

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Figure 9.

RESONANCE TUBE IGNITION – INTERNAL FLOWS

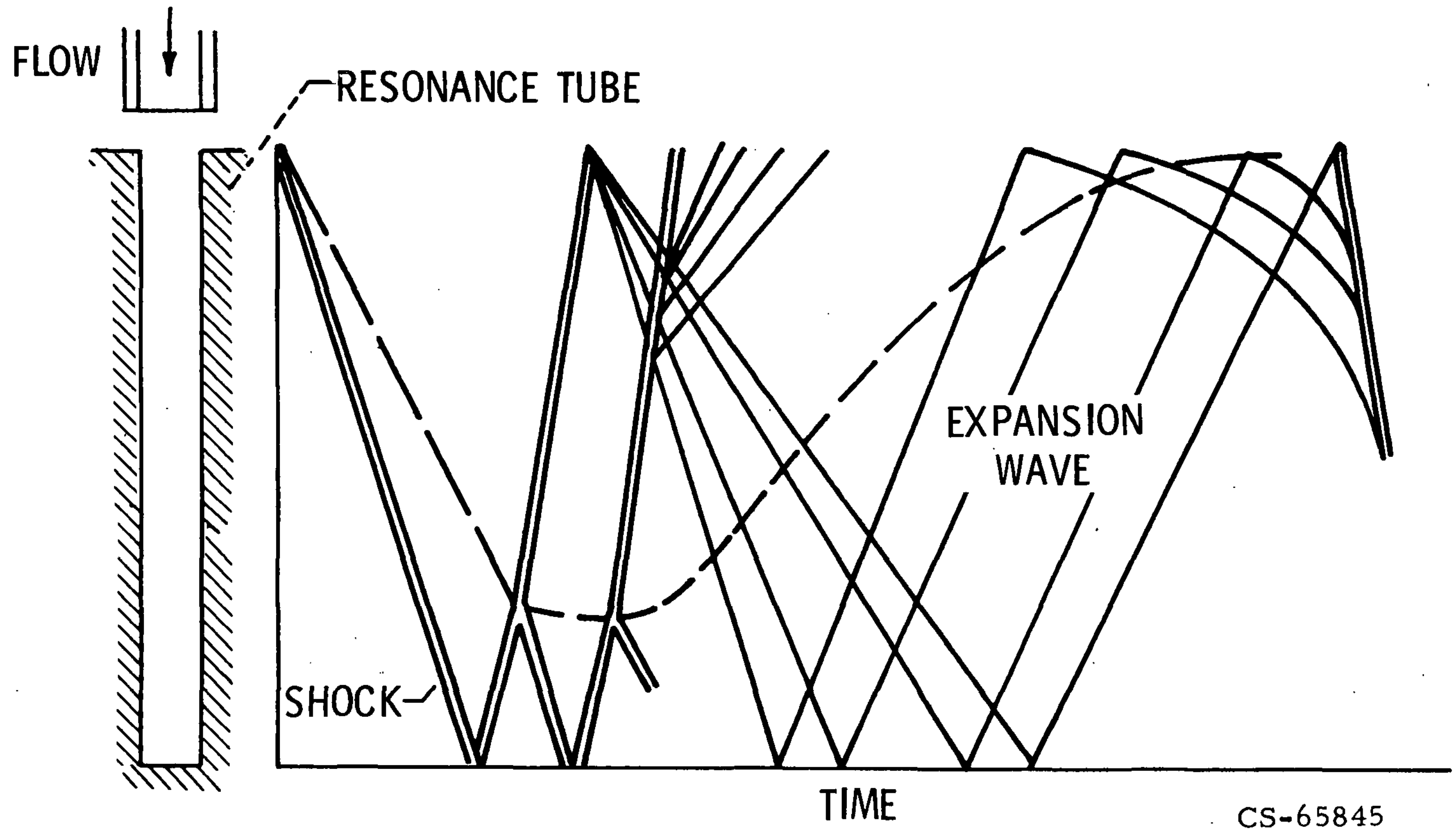


Figure 10.

RESONANCE TUBE IGNITION

TEMPERATURE IN RESONANT CAVITIES

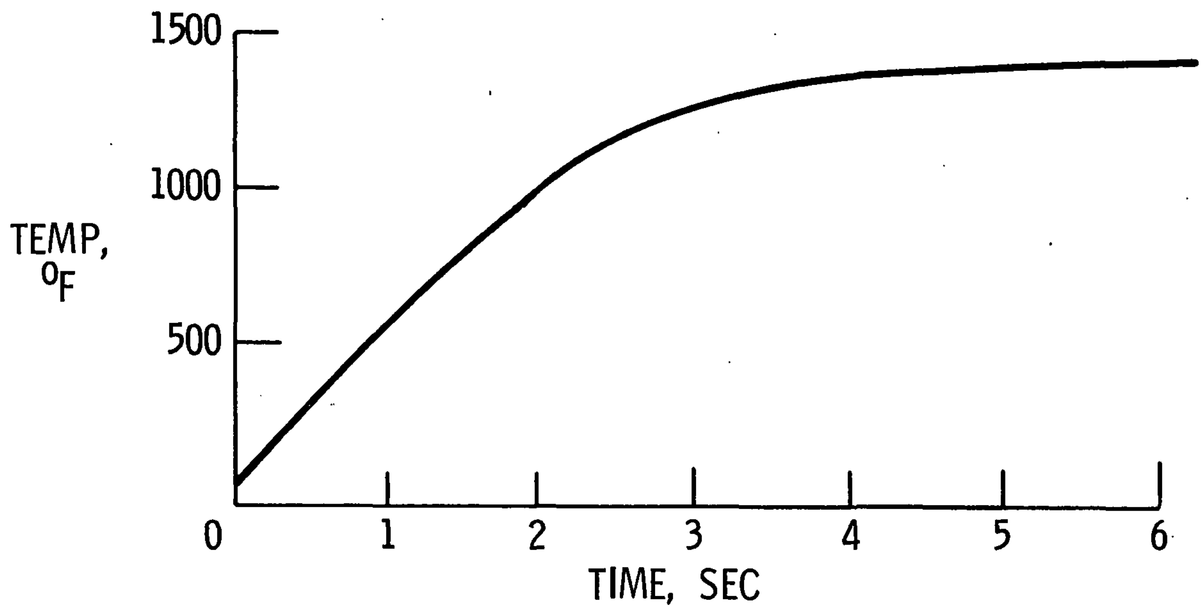


Figure 11.

CS-65839

FRACTURE IGNITION RIG

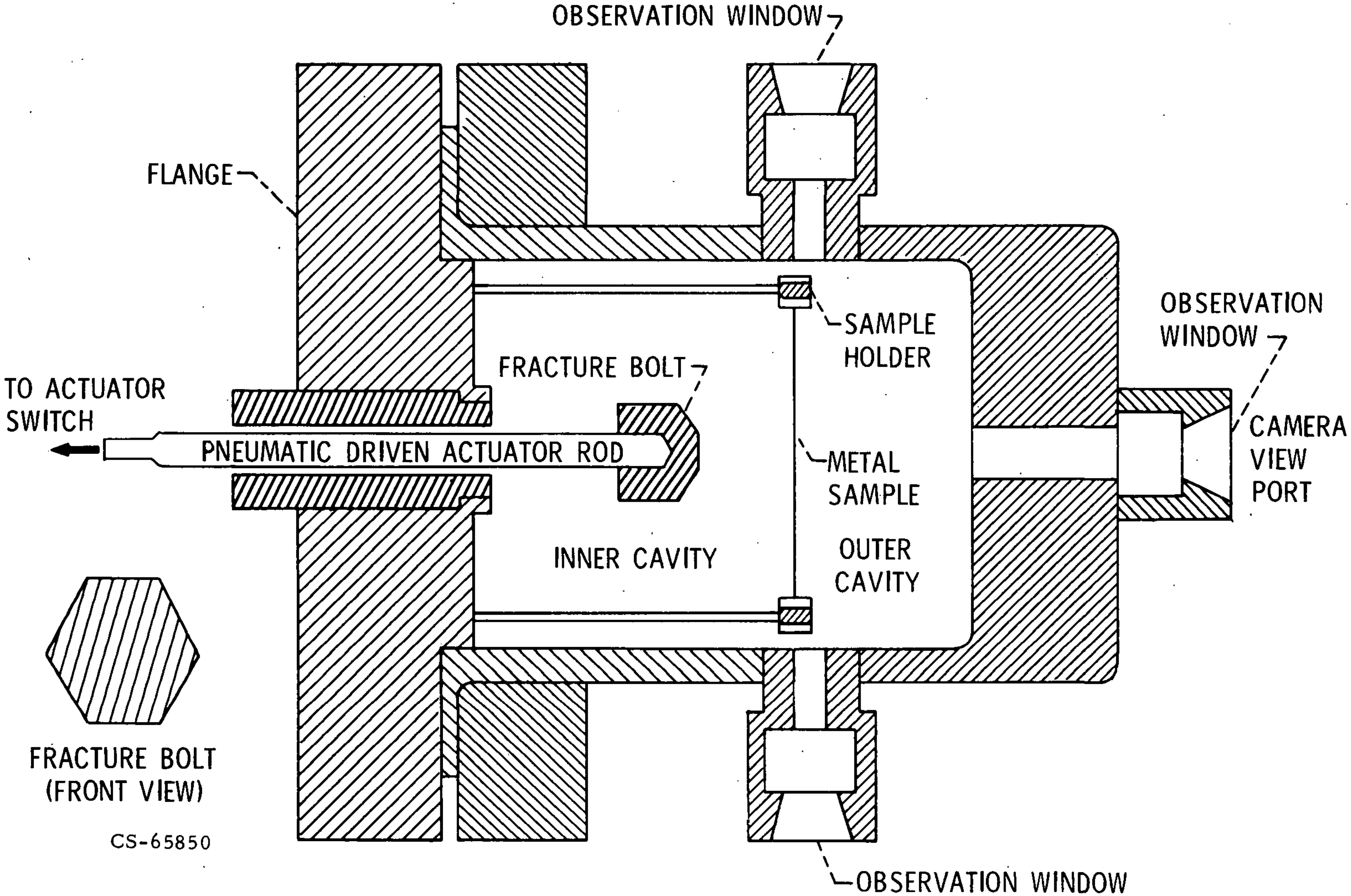
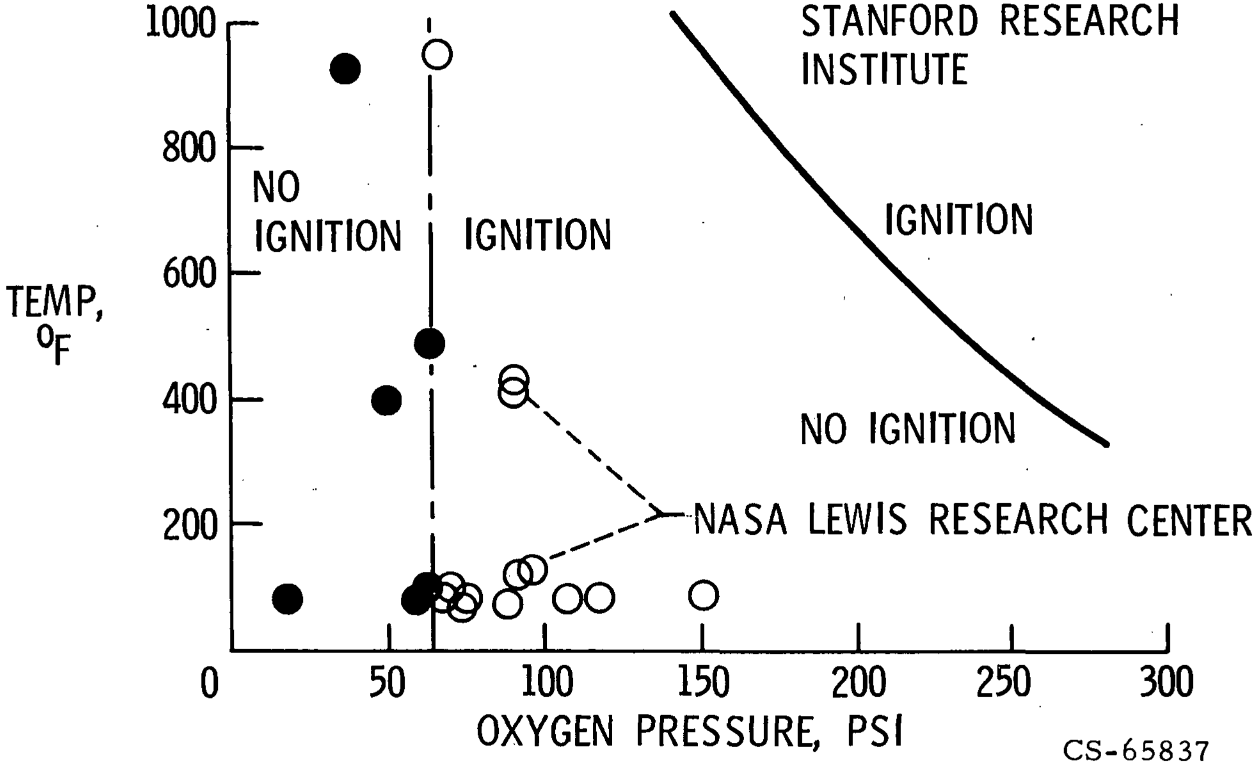


Figure 12.

EFFECT OF TEMPERATURE ON SPONTANEOUS IGNITION OF RUPTURED TITANIUM IN OXYGEN



CS-65837

Figure 13.

EFFECT OF OXYGEN CONCENTRATION ON IGNITION OF FRACTURED TITANIUM IN OXYGEN-NITROGEN MIXTURES

TEMPERATURE, 80^0 TO 90^0 F

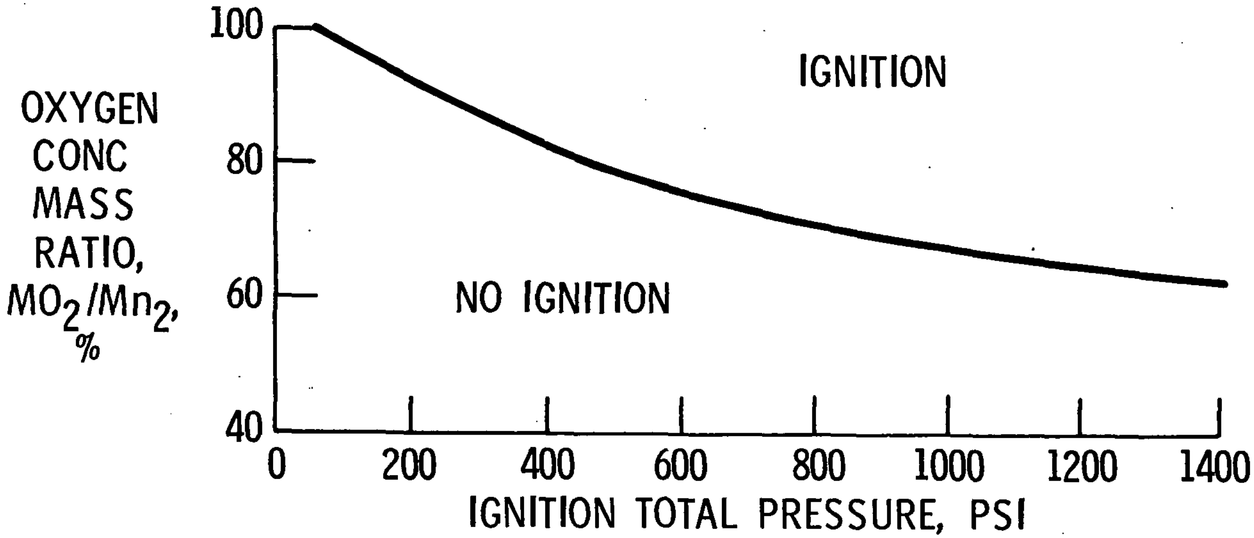


Figure 14. CS-65838

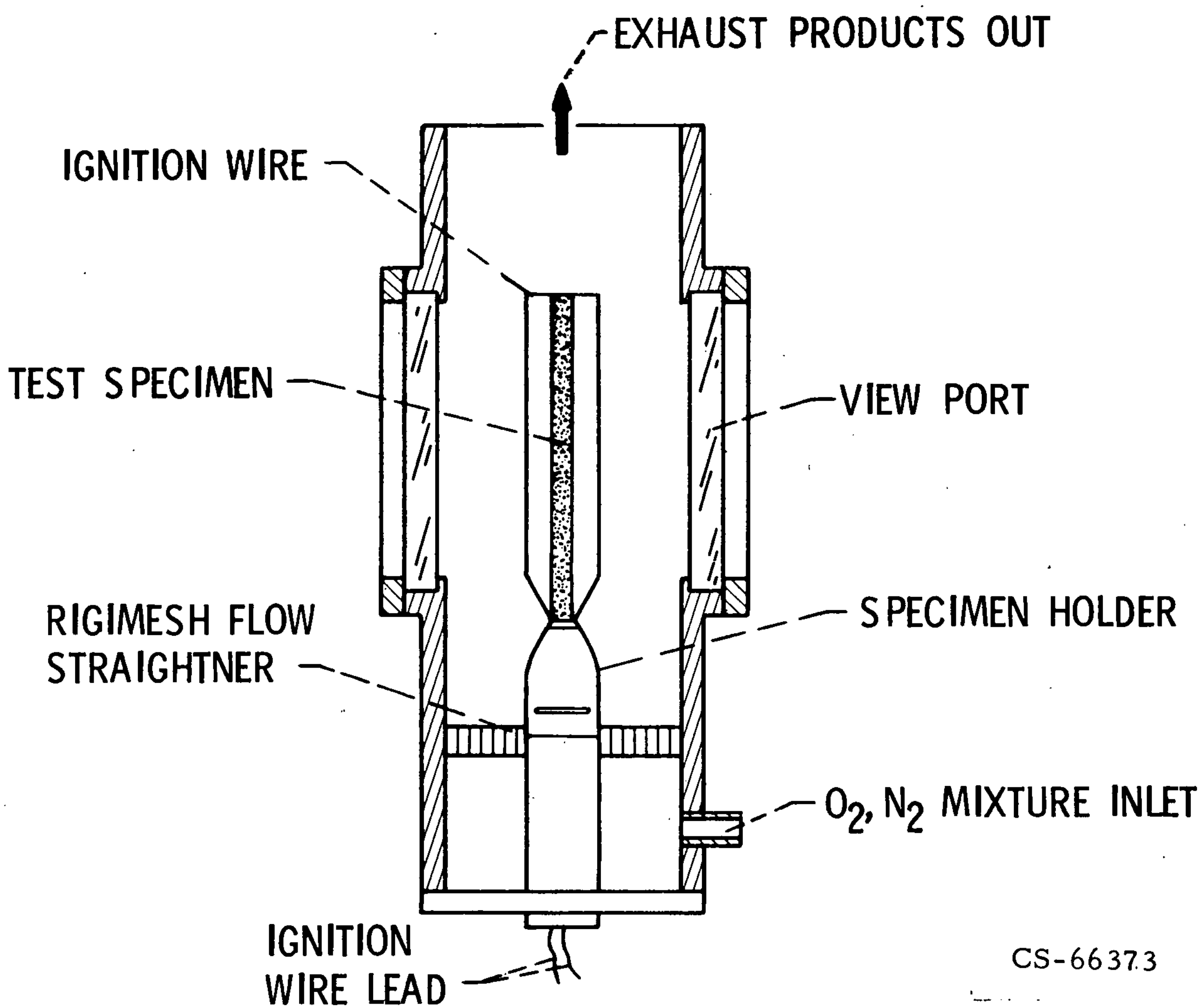


Figure 15. - Burning rate apparatus.

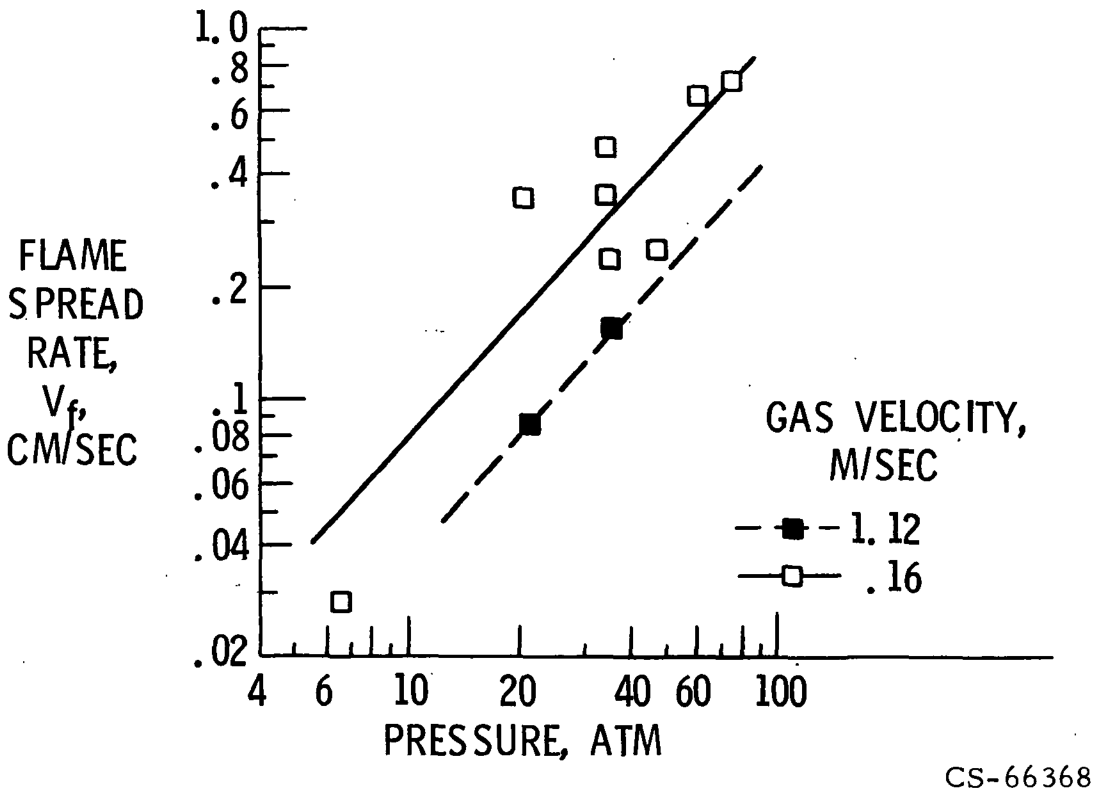


Figure 16. - Flame spread rate - teflon.

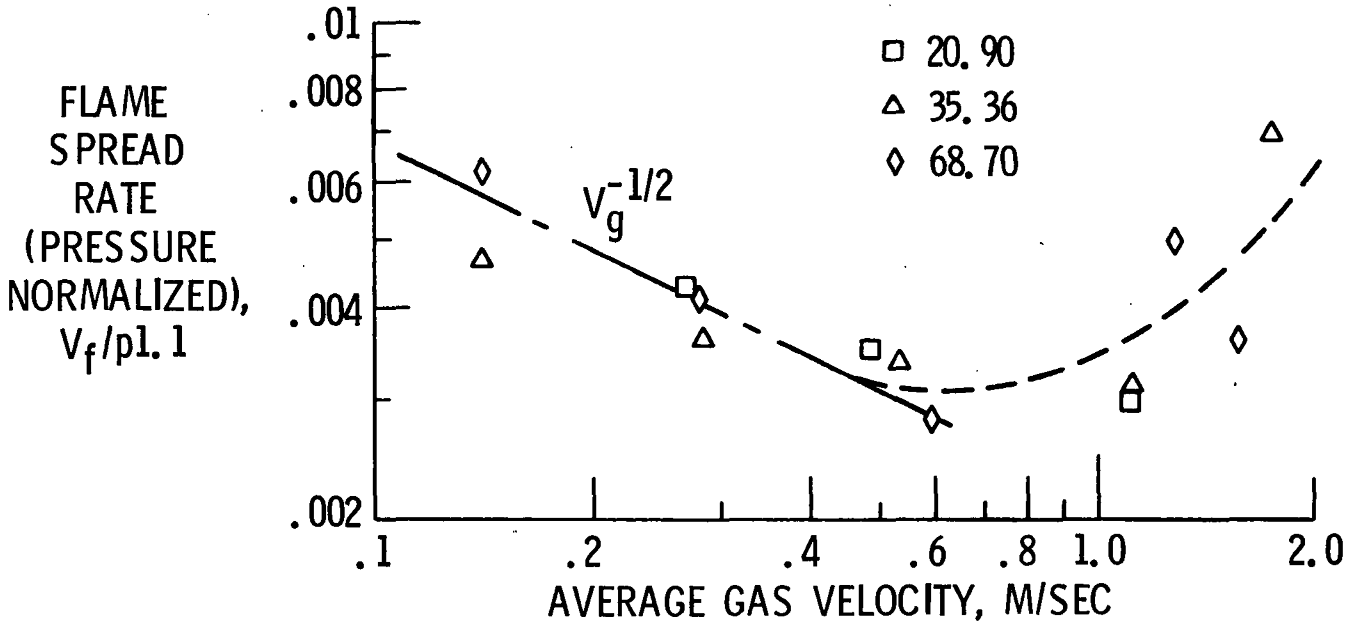


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Figure 17. - Flame spread rate - teflon.

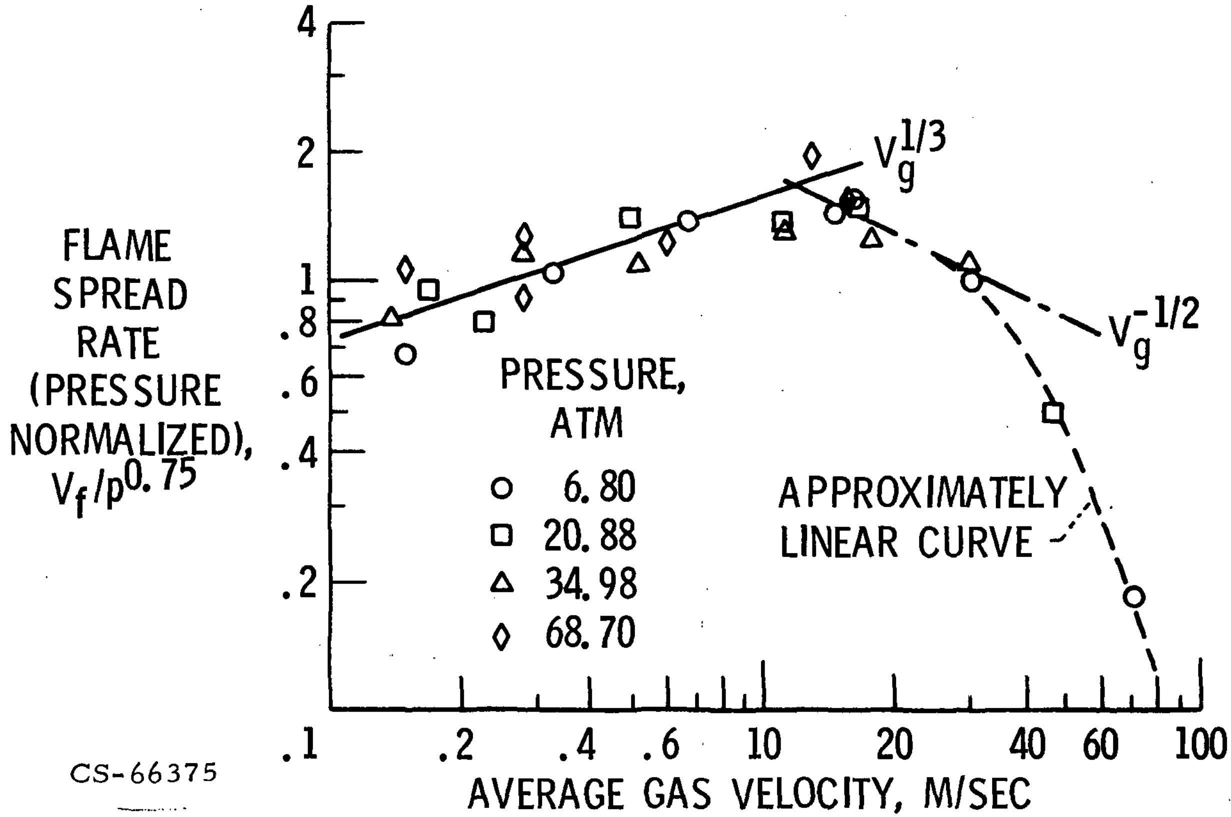

Figure 18. - Flame spread rate - polymethylmethacrylate.