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15 January 1963

A SURVEY OF INSULATION MATERIALS

CONTRACT NO. AF 33(657)-8890

TASK NO. 738103

PHASE I

1 October 1962 Through 31 December 1962

AEROJET GENERAL TIRE GENERAL

AEROJET-GENERAL CORPORATION
SOLID ROCKET PLANT • SACRAMENTO, CALIFORNIA
A SUBSIDIARY OF THE GENERAL TIRE & RUBBER COMPANY

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FOREWORD

All data reported herein was originally released in Aerojet-General Corporation, Solid Rocket Plant, Materials and Fabrication Report No. 339, entitled "A Survey of Insulation Materials", dated 8 November 1961. Data reported in Appendix B was released in Aerojet-General Corporation, Solid Rocket Plant, Materials and Fabrication Report No. 289, "A Survey of Rocket Insulation Test Devices, Insulation Performance, and Insulation Behavior", dated 23 April 1961.

Acknowledgement is made to the following named persons who contributed materially to the original reports: R. L. Keller, Development Engineer; A. A. Stenersen, Supervisor, Insulation Application Research and Development Section; E. G. Gras, Metallurgical Engineer; and J. P. Wilson, Technician.

This report was prepared under Contract No. AF 33(657)-8890, Task No. 738103, literature survey and compilation of unpublished materials information for inert propulsion components generated by the Solid Rocket Plant. This task is being coordinated at Aerojet-General Corporation, Solid Rocket Plant, by Alexander Kowzan, Nozzle Components and Project Support Department.

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ABSTRACT

A review was made of published reports and literature on the insulation materials to establish the status of the art in theory, formulation, testing, and processing; to establish the type of design data available and to provide an analysis of the available data. A major effort was made to obtain information on internal insulation materials.

Discussed in this report are the common theory of the ablation process, the status of heat transfer analysis of ablative materials, the test devices and testing techniques presently used for material evaluation and the status of development and processing of internal insulation materials. Performance data of internal insulation material from torch screening tests, plasma generators, subscale propellant test motors and full scale motor firings are presented. Significant performance data of nozzle insulation materials and external insulation materials are included. Physical and mechanical property data are shown for some nozzle and internal insulation materials.

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I. INTRODUCTION

Thermal protection of parts exposed to high temperatures is presently a major problem in the development of solid rocket motors and space vehicles. Nozzle components and the fore and aft end of solid propellant motor cases are exposed to the erosive conditions of propellant flames at temperatures as high as 6600°F. The skin temperatures encountered on re-entry to earth of space vehicles and nose cones is estimated to reach temperatures in excess of 10,000°F.

To provide thermal protection for the critical areas, a series of thermal protection systems such as heat sink, radiation, reflection, transpiration, and ablation have been investigated to some extent. Ablative insulation is currently considered the simplest, the most effective and reliable method for thermal protection of the exterior and interior of motor cases and for the nozzle entrance area and the exit cone.

The feasibility of thermal protection of missile parts by ablative insulation materials was at first clearly demonstrated on re-entry of nose cones in 1958. Since then extensive work has been conducted by governmental agencies and firms in testing and evaluation of the ablative properties of plastics and reinforced plastics. Some work has also been done to analyze the mechanism of ablation and to formulate elastomeric ablative materials. Several hundred pertinent articles have been published. These articles contain primarily information and test data on ablative materials obtained by model studies and laboratory testing. Little information has as yet been available on test data obtained at actual use conditions. A large number of solid propellant motors have, however, been test-fired at the Aerojet-General Corporation using ablative insulation materials. The quantitative data reported on the performance of ablative insulation materials on test firings of solid rocket motors are useful as design information. The status of work conducted on ablative insulation materials with regard to theory, formulation, testing and processing and quantitative performance data reported on insulation materials from full-scale motor firings, sub-scale propellant motor tests and material screening tests are discussed in this report. This work was conducted under Contract No. AF 33(600)-36610.

II. OBJECTIVE AND SCOPE

The over-all objective of this survey was to collect, tabulate and analyze published data obtained by various governmental agencies and Aerojet-General facilities during the testing of insulation materials intended for solid rocket motor.

The material design data of primary interest included ablation rates and erosion rates at varying exposure conditions, physical and mechanical properties, and data on heat transfer, formulations and processing.

The scope of the analysis was to establish a possible correlation of material performance data in the various tests and motor firings, to evaluate test equipment and attempt to establish the main factors that affect the rate of erosion and ablation at given and varying exposure conditions. The survey therefore, involves a review of:

1. Work conducted to determine the factors that affect the rate of erosion and ablation.

2. The development of test devices and testing techniques for ablation materials.

3. Performance data from full-scale firings, sub-scale test motors and screening tests.

4. Physical, mechanical, and chemical properties of insulation systems and their components.

5. Processing of insulation systems.

III. CONCLUSIONS

A. The literature on ablative insulation materials reveals that extensive efforts have been made in the development of test devices and in the evaluation of reinforced plastics for nose cone insulation.

B. The main physical and chemical reactions that take place during the ablation process are believed to be known, but the relative effect of the many parameters that determine ablation rates at given exposure conditions have not been determined experimentally.

C. Analytical solutions have been derived for the heat transfer in ablating materials assuming steady state conditions.

D. A number of torch test devices have been developed for laboratory screening and evaluation of ablative insulation materials. A round robin test program conducted to standardize an oxyacetylene torch test reveals poor correlation of test data obtained by the various devices involved. Oxyacetylene torch tests do not appear capable of screening insulators for rocket motors but have been found useful as laboratory tests in the development of ablative insulation materials.

E. Plasmajet tests appear to be useful for evaluation of nose cone and external insulation materials. Plasmajet test data on internal insulation materials do not correlate well with sub-scale motor data.

F. The test data of primary interest for the design of internal insulation profiles are the dimensional material loss rates or ablation rates.

G. Sub-scale propellant motor tests, which simulate the environments producted in full-scale motors, appear to be the most useful tests for evaluation of internal chamber insulation materials.

H. Detailed quantitative data on the performance of internal insulation in full scale motors have been reported only during the past two years and for relatively few motors.

I. A series of rubber-based materials have recently been developed for internal insulation of rocket motors. Sub-scale propellant motor tests show best performance for insulation systems based on nitrile-rubber as binder with either asbestos or boric acid as filler.

J. RITE Motor tests on the V-44 insulation material (GT&R) show that this material has a decreasing rate of ablation with time of exposure. The rate of ablation increases markedly with chamber pressure in the range from 200 to 400 psig.

K. Polyurethane insulation materials have shown good performance in EAGLE and GAM-87A motors.

L. Graphite-phenolic and glass-fiber phenolic insulation systems are currently the best available materials for insulation of nozzle exit cone and entrance section respectively.

IV. RECOMMENDATIONS

A. Programs for development and evaluation of internal insulation systems should include determinations of the thermophysical properties of promising materials. These properties are needed for heat transfer analysis used in the design of insulation profiles.

B. In the development of ablative insulation materials, efforts should be made to determine experimentally the main factors that affect the rate of ablation and erosion and the experimental data correlated with theoretical heat transfer data and chemical thermodynamic property data of the material components used.

C. The development of improved insulation systems should be directed toward systems which can be more easily processed.

D. Improved tests are needed particularly for screening of internal insulation materials.

E. Sub-scale propellant test motors such as the RITE Motor should be used for evaluation of nozzle and internal insulation systems.

F. Efforts should be made to develop a sub-scale test motor that is more versatile and less costly to operate than the RITE Motor. The motor must be capable of simulating full-scale motor firing conditions and should be capable of testing a series of materials in one firing.

G. To provide useful design data, ablative insulation materials should be tested for ablation and erosion rates both by weight and dimension.

V. DISCUSSION

A. TERMINOLOGY

The published literature on ablative materials shows that the terms used to describe ablation phenomena are different at various agencies. At the Aerojet-General Corporation, the terms differ to some extent with project and facility. The need for a standardized terminology is realized at agencies such as the Bureau of Standards and ASTM (American Society for Testing Materials). Committees have therefore been appointed to standardize the terminology for ablation materials in conjunction with standardization of flame tests. Until a standardized terminology is available it is necessary to define the terms used in publications and reports. Definitions of terms used in this report are listed in Appendix A.

B. THE ABLATION PROCESS

1. Physical and Chemical Reactions in the Ablating Zone

The literature review showed that only some aspects of the mechanism of ablation have as yet been investigated. The publications on ablative materials (about 500) are primarily concerned with the high temperature properties. Some studies, however, have been made on the heat transfer mechanism and the thermophysical state change reactions involved. Only a few preliminary investigations have been made on the thermochemical reactions that take place. The most informative publications on the ablation process, see references, indicate that the main physical and chemical reactions involved are as follows:

a. Absorption of Heat to Reach the Ablation Temperatures

When an ablative insulation material, consisting of a polymeric binder and an inorganic filler, is exposed to an environment such as the propellant flame or exhaust, some heat energy is at first abosrbed by the material before any state changes take place. The amount of heat energy absorbed depends primarily on physical properties of the material such as thermal conductivity and specific heat.

b. Absorption of Heat by State Change Reactions

As soon as the surface layer of the material has reached a certain temperature, binder and filler components start to decompose or ablate. The initial ablation temperatures vary greatly with type of binders and fillers used. Heat energy is absorbed during physical state changes such as sublimation, fusion, and vaporization. Concurrently, a series of chemical reactions take place. The filler components formed react with each other and with components of the propellant combustion gases. The heat energies absorbed and/or given off during these reactions are dependent on the heat of decomposition and heat of formation of the reactions. However, the rate at which these reactions take place is a predominant factor. The chemical reactions that take place are dependent on temperature and pressure and may be governed to some extent by catalysts added to the materials.

c. Char Formation

The result of the initial physical state changes and chemical reactions is the formation of solid and liquid decomposition products at the outer layer of the ablating material. This char layer increases in thickness and changes in composition and physical properties with time of exposure. Generally, the char layer formed provides increased thermal and mechanical protection with time of exposure.

d. Transpiration Cooling

The gases formed in the inner decomposing material layer are emitted (transpire) through the pores of the char residue and provide a counter-flow of gases against the impinging particles. The gases emitted are in general relatively cool. Therefore, mass transfer cooling takes place between the gases emitted and the hot propellant combustion products (transpiration cooling), thereby providing a protective shield or barrier against the impinging particles. The effectiveness of this shield as a protective barrier depends on the rate, the amount, molecular weight, and the heat capacity of the gases formed.

e. Radiation Cooling

In addition to the heat dissipated through absorption, some heat is re-radiated. The amount of heat re-radiated is influenced by the properties of the char and its surface temperature. The incorporation of radiation "blocking" agents have been found effective in increasing the radiation cooling effect of insulation materials.

2. Mechanical Factors

The rate of decomposition of the ablative material is an important factor in obtaining a minimum rate of ablation. If the rate of decomposition is very fast the ablating surface layer may be forced to expand in a similar manner as expansion of plastic foams. This results generally in very little heat absorption. On the other hand, if the decomposition is very slow, the material may be eroded away mechanically before any heat absorption takes place. The mechanical properties of the ablative materials at high, elevated, and ambient temperatures affect the insulation performance in several ways. A highly crosslinked, rigid, structure has been found desirable to prevent decomposition of the binder into liquid components and for the formation of effective chars. However, an internal insulation material which is bonded to the chamber and the propellant may be subjected to high stresses. A flexible material has therefore been found to be essential in order to avoid mechanical failures. Spalling, cracking, or flaking may also occur below the material softening temperature of rigid insulation materials due to vibrations. Separation of thermally softened material pieces may be caused by impact erosion of particles in the propellant exhaust.

3. Exposure Conditions

a. Propellant Flames

The environmental exposure conditions produced by propellant flames and exhaust differ considerably with the various type propellant currently used in solid rocket motors. An aluminized propellant produces generally more erosive conditions than a non-aluminized propellant. An oxidizing atmosphere may be detrimental to some insulation systems and advantageous to others. The variables of this type environment may be divided into physical, chemical and mechanical factors. Some of the variables of propellant exhaust affecting the rate of ablation are believed to be:

(1) Density of constituents

(2) Concentration of constituents

(3) Velocity of constituents

(4) Temperature

(5) Total mass flow rate

(6) Atmospheric condition (reducing, oxidizing)

b. Aerodynamic Heating

The environments encountered by nose cones on re-entry differ widely from propellant exhaust conditions. The main factors considered in evaluation of nose cone materials are total heat flux and mass flow rate.

4. Formulation Variables

The ablative insulation materials consist generally of an organic polymeric binder and an inorganic filler incorporated as a pigment, filler, or fabric.

Organic polymers are used as binders to provide the required mechanical properties over a wide temperature service range because of their low thermal conductivity and their ability to provide thermal and mechanical protection by the formation of an erosion resistant char. The char formation and properties of the char are influenced by such factors as the chemical structure of the polymeric binder, its crosslinking, unsaturation, relative concentration of aliphatic and armomatic carbon atoms, concentration of H, O and other elements, and type of polymer linkages.

Highly crosslinked binders are generally desirable because these binders on heating to high temperatures do not melt but decompose primarily in the solid state. The partially degraded material inside of the char may therefore have useful mechanical properties at high temperatures. A large concentration of aromatic, condensed aromatic, and certain cyclic rings in the binder is desirable because a relatively large amount of heat energy is required to break or alter their chemical bonds.

The function of the fillers is to absorb heat energy primarily by state change reactions. The rate at which these reactions take place is a decisive factor. Composition parameters that influence the rate of ablation may therefore be divided into physical, chemical and mechanical properties and characteristics as listed in the following table:

FORMULATION VARIABLES

Physical Factors	Chemical Factors	Mechanical Factors
1. Density	1. Chemical structure of binder and filler	1. Tensile strength
2. Thermal conductivity	2. Crosslinking	2. Elongation
3. Specific heat	3. Type polymer linkage	3. Binder-filler bond strength
4. Thermal diffusivity	4. Elemental concentration of constituents (C, H, O, N, etc.)	4. Filler and grain orientation
5. Heat of sublimation, fusion and vaporization		

C. THEORETICAL HEAT TRANSFER ANALYSIS OF ABLATIVE MATERIALS

The heat transfer mechanism of char-forming ablative materials is very complex (25). The char layer complicates the heat transfer problem because it introduces a second phase between the solid and gaseous boundary layer and because of the flow of gases from the decomposing material through the char. A problem encountered in conducting heat transfer analysis using the equations derived is the lack of accurate thermophysical property data such as thermal conductivity and specific heat at high temperatures and of heat and temperature of ablation. In addition, the decomposition products formed and emitted through the char are difficult to analyze and are generally not known.

To conduct a heat transfer analysis for a material that ablates with formation of a char, it is necessary to make a series of assumptions including:

a. A constant heat of ablation

b. A constant temperature of ablation

c. Steady state conditions

d. No overall shrinkage in decomposing material and char

By use of analytical model studies, equations have been developed and evaluated to show the relationship between ablation rates and char properties for various conditions simulating aerodynamic heating. Some of the conclusions reached by model studies seem to agree with experimental data.

The Aerojet-General Corporation has recently conducted a heat transfer analysis to investigate the relative effect of various thermophysical properties on the ablation rates. The analytical solutions derived are not included in this report. However, some results of this analysis are shown in Figures 1, 2, 3, 4 and 5. It is noted that variations in the heat of ablation, the temperature of ablation, and the specific heat greatly affect the rate of ablation while a variation in the thermal conductivity has a negligible effect.

D. TEST DEVICES AND TESTING TECHNIQUES

1. Literature Review

A review was made of test devices and testing techniques used in the development, evaluation, and analysis of ablative insulation materials. This review showed that major efforts have, to date, been done in the development of test devices to determine ablation rates at environments simulating aerodynamic heating and propellant exhaust. Attempts are currently being made in the design and development of new improved test devices and instruments to analyze materials char forming ability, heat absorbing ability, gaseous decomposition products formed during the ablation process, and composition and nature of propellant exhaust. The literature revealed minor efforts to develop improved tests for evaluation of the physical properties of materials at elevated and high temperature. Such data are needed in heat transfer analysis and analysis of the major factors that determine the rate of performance of ablative materials. Test devices to determine char properties at the high temperatures encountered in exposure to propellant exhaust have not been reported. The test tools currently used in the development and evaluation of ablative materials are briefly discussed below.

2. Devices for Testing of Ablative Properties

a. Oxyacetylene Torches, Plasma-arcs and Sub-scale Motors

A comprehensive survey of torch test devices, plasma generators and subscale propellant motors was made and is discussed in Appendix B.

3. Differential Thermal Analysis (DTA)

DTA is used as a guide in material development to determine the heat absorption potential of materials. Essentially, this method involves the use of reference and unknown materials heated in separate containers at a fixed rate, as illustrated in Figure 6. Comparison of the temperature difference, which is measured by using a differential thermocouple whose thermal e.m.f. is continuously plotted by a recording potentiometer, usually versus time, determines their comparative heat absorption potential. Exothermic as well as endothermic processes can be recorded.

The use of DTA in determining absorption potential is limited due to the fact that many DTA patterns are too complex or diffuse to be quantitatively treated. The many parameters and unknown variables (experimental and theoretical) result in uncertainty.

4. Thermogravimetric Analysis (TGA)

Thermogravimetric Analysis is also used as a guide in material development. By this analysis the residual weight of sample material is measured continuously as the sample is heated at a controlled rate. In modern practice, a virtually linear function of residual weight is automatically recorded on a time basis or on a temperature basis. In either case, the ultimate record is a plot of residual weight fraction versus the environmental temperature in a region near the sample. The effect of different heating rates on the TGA, due to its reproducibility and correlation to the extent of degradation, is at present considered more reliable than DTA in obtaining the absorption potential of materials.

5. Emission Spectra and Chemical Analysis

The initial comprehensive studies of the chemical reactions involved in the ablation process have been made by Stanford Research Institute (26, 27). These studies include investigations of techniques for sampling the gaseous boundary layer of an ablating resin in an argon-stabilized plasmajet and the use of emission spectra for analysis of the boundary layer. The gaseous decomposition products of several resins were determined by mass-spectrographic analysis. The results show, however, no particular correlation between ablation performance of a material and either its emission spectra or the products of ablation.

E. INTERNAL INSULATION MATERIALS

1. Formulation

Organic polymers have inherently good thermal insulation properties and ablate when exposed to high temperatures. Elastomeric polymers such as polyurethanes and nitrile rubber have therefore been used for lining and internal insulation of solid rocket motors. In recent years it has been found that the ablative properties and the erosion resistance of such polymers can be greatly improved by the incorporation of fillers or reinforcing agents which have high heat absorption potentials.

The approach used in the development of internal insulation has to date primarily involved evaluations of binder-filler systems for heat-absorbing ability by DTA and for char-forming ability and ablative properties by TGA and oxyacetylene torch tests.

Nitrile rubber systems have been found particularly promising as binders by various rubber companies. The Garlock 7765 material, a nitrile rubber-silica system, has been used as a reference internal insulation material for several years.

Improved nitrile rubber systems have recently been developed by the Mare Island Naval Shipyard (compound 388-58 and 388-98) and by the General Tire and Rubber Company (V-44 and V-52). The improvement in ablative properties of these systems are claimed to be due primarily to improved processing techniques.

Phenolic resin-nitrile rubber binders have, by some companies, including the U.S. Rubber Company and the Goodyear Tire and Rubber Company, been found to provide improved char properties for more efficient transpiration cooling. A series of fillers, such as listed in Table I, have been investigated for these binders. The chemical thermodynamic properties given for the fillers in circular 500, National Bureau of Standard are included in the table. The filler investigations have shown that boric acid and potassium oxalate provide better performance than asbestos in this type binder system. Boric acid and potassium oxalate are believed to be efficient filler because of their low decomposition temperature and high rate of decomposition at the given exposure conditions. The temperature in the decomposing layer of these systems, when exposed to an oxyacetylene torch flame, is reported to be approximately 800°F.

Polyurethane systems have been investigated to some extent as internal insulation materials by the Aerojet-General Corporation. The systems evaluated have been formulated primarily for use as chamber liners and not with regard to optimum ablation and erosion resistance.

Internal insulation materials based on elastomeric phenolic resins have recently been developed by Nobell Research Laboratory. The compounds developed contain a low filler concentration and are applied by spraying. The ablative properties of these systems are similar to those of rubber-based systems.

The reported programs for development of internal insulation materials include only a few attempts to formulate ablative materials with regard to the thermochemical and thermophysical properties of fillers and binders. Such an approach appears to be most useful in order to advance the state-of-the-art and to achieve a significant improvement in the performance of ablative insulation materials. Research programs are in particular needed to provide experimental data for confirmation of current theories of the mechanism of ablation. Because of the many variables involved, a statistical design of formulations and a statistical analysis of performance data appear necessary to establish the essential factors that determine erosion and ablation rates of the given environmental conditions.

2. Ablative Properties

a. Oxyacetylene torch tests

A large number of rubber insulation compounds formulated by MINS (Mare Island Naval Shipyard) and by GT&R (General Tire and Rubber Company) have been screened for ablative properties by a torch device developed by GT&R. Test parameters and exposure conditions of this device are shown in Table II. The device has an oscillating feature that is not common in torch testing. The main performance criteria used are the dimensional material loss rate, the thickness of the char formed, and the temperature rise on the back side of the 1/4 inch thick test specimens used. Performance data of some internal insulations are shown in Table III. The newly developed V-52 has shown best performance in this torch test.

A series of internal insulation materials have also been evaluated by the RIME test, Aerojet-General Corporation, Azusa, California. The RIME test has different and more severe exposure conditions than the GT&R torch. The oxygen-acetylene ratio is 1.2/1.0 as compared to 1.076/1.0 for the GT&R torch and the total gas flow rate is 720 cu ft/hr as compared to 72 cu ft/hr for the GT&R torch. Performance data for the best internal insulation materials evaluated by this device are shown in Table IV.

b. Plasma Generator Test

Plasma generators are designed to produce very high flame temperatures and high gas velocities and are seldom used for evaluation of internal insulation materials. A few internal insulators have, however, been evaluated in the plasmatron device, Azusa. The test data obtained are of interest for comparison with sub-scale propellant motor data. Some of the best test results reported are shown in Table V.

c. Sub-scale Propellant Motor Tests

(1) RITE Motor Tests

The RITE (Rocket Insulation Test Evaluation) motor was designed for evaluation of internal insulation materials. Exposure conditions similar to those of full scale firings are obtained by use of same propellant and same firing parameters as in the full scale chambers.

A total of 150 RITE Motors have been fired to evaluate the erosion resistance of a number of insulation materials. The test data obtained for eight of the best materials evaluated under duplicate conditions are shown in Table VI. The main performance criteria are the total losses in weight and thickness of the material and the corresponding Thickness Loss Rate (TLR) and Mass Loss Rate (MLR). The TLR is of primary interest to the design engineer in establishing the internal insulation profile and design safety factors. A rating of the eight materials tested at the established conditions with regard to TLR is shown in Figure 7. It is noted that two relatively new materials, V-52 (7242-IV-62A) and M-707 show better performance than the V-44 material which has been test-fired and shown good performance in several full scale motors. Figure 7 also illustrates the importance of a low density insulation material by the (TLR) X (density) product. This product is used as a guide in selection of the material that by weight provides the best insulation.

The V-44 material has in particular been evaluated by RITE Motor tests. The effect of chamber pressure on the rate of erosion (TLR) and the rate of erosion (TLR) vs time of exposure for this material are illustrated in Figures 8 and 9 respectively. The firing durations used in Figure 8 are approximately eighty-five seconds. The flame temperature of the propellant used at pressures above 500 psig, is approximately 400°F higher than at the lower pressures. It is noticed that the thickness loss rate increases rapidly with increasing chamber pressure in a pressure range from 200 to 400 psig, while an increase in pressure from 400 to 800 psig has only a slight effect on the thickness loss rate.

In Figure 9, thickness loss rate values are plotted vs time of exposure for the periods 6, 16, 33 and 45 seconds. The thickness loss rate is high during the first seconds of exposure and decreases with time for the firing durations used. The main reason for a decrease in the rate of erosion is believed to be due to increased thickness of the char layer with time of exposure providing increased thermal protection through transpiration or mass transfer cooling in the char layer.

(2) ABL and ARC Test Motors

The ABL (Alleghany Ballistics Laboratory) and ARC (Atlantic Research Corporation) have evaluated a large number of internal insulation materials by their test motors.

A "Round Robin" Test Program conducted to evaluate the relative performance of the V-44, USR-3015 and NOL-3098 materials in these and the RITE Motor gives some information as to the effect of different propellant exhaust on insulation material performance. Standard first stage POLARIS propellant was used in the RITE tests. The TLR values (char rates) for the three materials in the three test motors are shown in Table VII. The ABL test data show best performance for the USR-3015 material and the poorest performance for the NOL-3098 material. The ARC data show best performance for the V-44 material and poorest performance for the USR-3015 material. The difference in material performance is believed to be due to differences in propellant flame temperature and composition of propellant exhaust.

d. Full Scale Motor Data

(1) POLARIS Motors

Erosion rate data on insulation materials obtained at actual use conditions are of interest, both as material design data and in the development of useful screening tests and improved sub-scale test motors. A particular effort was therefore made to obtain quantitative performance data for correlation purposes. POLARIS test firings were of particular interest because of the relatively large number of motors fired. Practically all memos and reports on POLARIS insulations were therefore reviewed. Performance data for POLARIS Motors are shown in Table VIII. Data for nozzle insulation are also included in this table. Firing reports issued during 1960 and 1961 provide detailed information on the amount and rate of erosion for the entire area of forward and aft end enclosures. These areas are divided into sections and stations as shown in Figure 10. The dimensional material loss rate (MLR) for the V-44 material at the various stations of first and second stage A3 motors are shown in Tables IX, X, and XI. The average MLR for the various stations in the second stage motor aft closure is approximately .06 in/sec. The value for the first stage motors is .18 in/sec.

(2) MINUTEMAN Motors

The configurations and profiles of the forward and aft closures of the second stage MINUTEMAN Motor are similar to those of the POLARIS motors. The insulation systems evaluated in the MINUTEMAN Motor include Garlock 7765, and the V-44 material. The dimensional material loss (removal) rate of V-44 at the various stations in MINUTEMAN aft closures are shown for two motor firings in Table XII. The average dimensional material loss rate for two motors is 0.18 in/sec.

(3) Miscellaneous Motors

The performance data reported for the GAM-87A, the EAGLE and HAWK motors were also reviewed. A comparison cannot be made of the material performance data in these motors with the POLARIS and MINUTEMAN motors because of the different propellant and the different firing durations involved. The polyurethane system used for insulation of the EAGLE and HAWK motors appear to have as good performance as nitrile rubber insulators and should be of particular interest for internal insulation of rocket motors because of their ease of processing, (casting, spraying) and their good mechanical properties at low temperatures.

3. Mechanical and Physical Properties

The mechanical property requirements of internal insulators vary considerably with the dimensions and type of motor cases. A high elongation seems to be essential for insulation materials used in filament wound chambers. This has, in particular, been demonstrated by ABL. The use of insulators with a uniaxial elongation of approximately 15% in filament wound test chambers has repeatedly resulted in rupture in the insulation on chamber hydrotesting at approximately 200 psig.

Investigations are therefore being made of the stress-strain behavior of rubber insulators by various missile firms. Bi-axial and tri-axial tensile-elongation tests have recently been given particular attention. To avoid mechanical rupture in the internal insulation, materials with a uniaxial elongation of approximately 100%, at ambient temperature, are currently being used in filament wound motors. The reported mechanical properties of some of the best internal insulations developed to date are shown in Table XIII. The NC-1 material has shown good performance in ABL test motors but is apparently no longer considered a candidate internal insulation materials because of its low elongation.

Physical and thermophysical properties, in general, have not been determined by the firms engaged in the development of internal insulation materials. The Aerojet-General Corporation, Azusa, has however, determined the thermal conductivity, specific heat, heat and temperature of ablation for some internal insulation materials. Available data on the thermal conductivity and specific heat are included for the materials listed in Table XIII.

F. EXTERNAL INSULATION MATERIALS

The POLARIS and the MINUTEMAN missiles require external chamber insulation for thermal protection against aerodynamic heating of second and third stage motors respectively. Underground launching of the MINUTEMAN missile also necessitates insulation of its first stage motor. Ablative insulation is considered to be the most effective and reliable external insulation method because the skin temperature of these motors may exceed 1000 or 1500°F. Data from flight tests are, however, not yet available to confirm estimated skin temperatures.

The first, and apparently the only major effort to develop an external insulation material has been made on the MINUTEMAN Program. Sprayable ablative coatings have shown much promise with regard to ease of processing surface smoothness, mechanical and ablative properties. An alternate type material, also considered for external insulation of the second stage POLARIS A3 Motor is a cork compound that is prepared by molding and cut into a tape. The tape is applied by adhesive bonding. Apparent disadvantages of the cork tape is a high material cost, and a problem in obtaining a satisfactory bond to the chamber as well as a smooth surface.

Ablative properties of external insulation materials have been evaluated in plasma-arc tests. The data for six materials in Table XIV show best performance for the DC-651 material. Physical and mechanical properties for these external insulation materials are shown in Table XV and XVI.

G. NOZZLE INSULATION MATERIALS

A review was made of the literature on nozzle insulation materials to establish the status of material development and testing techniques. It was found that the literature gives very little information on the chemical reactions that take place during the ablation of these materials and that only minor efforts have been made to formulate insulators for the nozzle entrance section and exit cone. A large number of tests have however been run to provide engineering data on the ablative properties and erosion resistance of commercial resin systems with organic and inorganic fiber reinforcement. Oxyacetylene torch devices and plasma generators have commonly been used in these evaluations. The Tables XVII, XVIII, and XIX show test data for the best nozzle insulation materials evaluated at the GT&R torch test facility and the Azusa and Sacramento plasma-arc facilities respectively. The phenolic resin-graphite cloth systems have in general shown best performance as insulators for nozzle entrance sections while the phenolic resin-silica-cloth (fiber) systems have shown best performance in nozzle exit cones.

An evaluation of organic and inorganic fiber reinforcement in various resin systems was made by the University of Chicago using a plasma-arc test device. The results, illustrated in Figures 11 and 12 show that organic fiber reinforcement has superior erosion resistance (low ablation rates) at a high heat flux level while inorganic fibers provide the best erosion resistance at a relatively low heat flux level. The good performance of the organic fiber-reinforced resins at the high heat flux level is believed to be due to transpiration cooling by low molecular weight gases such as hydrogen, that are formed on decomposition of the organic fibers. The rate of decomposition of the fibers into small molecular weight gases, which is a function of temperature, is too low to be effective at the low heat flux level used.

H. CORRELATION OF PERFORMANCE DATA

A comparison has been made of the discussed performance data from oxyacetylene torch tests, plasma generator tests, sub-scale and full-scale propellant motors to establish the most useful tests for insulation material evaluation.

Oxyacetylene torch test data from a number of torch test devices have in particular been investigated in conjunction with the NOL-ASTM standardization program for oxyacetylene torch testing. This program, sponsored by the Navy's Special Project Office, involves panel tests on different ablative insulation materials and a statistical analysis of the test data. Test data from the RIME Facility and the GT&R torch test facility are included in this correlation study. Results to date show a poor correlation of performance data between all torch test devices involved.

A similar test program is underway for evaluation of plasma-arc test devices. Analytical data from this correlation study have not yet been made available.

Attempts to establish a correlation between published plasma-arc performance data from different facilities showed that a comparison could in general, not be made of the reported data due to lack of information on the materials compositions, differences in testing conditions, and differences in the type of data reported. Ablation rates are in general reported as dimensional values. However, ablation rates are by some facilities reported as average weight loss values.

A good correlation could not be established between either oxyacetylene torch test data and plasma-arc test data with sub-scale propellant motor data. It is to be noted that materials such as SMR6-11 showed outstanding performance in the plasmatron test, and relatively poor performance in the RITE motor.

Sub-scale propellant test motors seem to provide reliable insulation materials performance data that can be correlated with full-scale motor data. Sub-scale motor tests are used extensively by the Alleghany Ballistics Laboratory, the Atlantic Research Corporation and the Aerojet-General Corporation.

The RITE motor is the first sub-scale test motor designed by the Aerojet-General Corporation for evaluation of internal insulation materials at simulated full-scale motor firing conditions. Comparative test data from the RITE motor and full-scale motors are to date available only for the V-44 material. Figure 13 shows the average TLR values obtained for this material in the RITE motor at simulated first and second stage POLARIS A3 test conditions and the average TLR for aft head insulation of the corresponding full-scale POLARIS motors. A good correlation seems to exist between the TLR in the RITE motor and the full-scale motors with regard to the firing parameters used. The average TLR data for V-44 in the second stage MINUTEMAN motor and in the GT&R torch device are included for comparison.

I. ABLATIVE NOZZLE THROATS

The evaluation of fiber-reinforced plastics and rubber insulations in torch test and plasma generators have indicated that it is feasible to develop ablative nozzle throats. The following type ablative materials may be considered:

1. Materials that Ablate with a Constant Rate of Ablation

Some materials, such as fluorocarbon polymers, have been reported to ablate without the formation of a char. Other materials ablate with the formation of a very weak char that is immediately removed from the ablative surface by high velocity propellant exhaust. These type materials will apparently assume a constant rate of ablation at constant environmental conditions. A problem involved in such a development is to achieve a sufficiently low ablation rate.

2. Materials with Decreasing Rate of Ablation

Insulation materials based on rubber and phenolic resin-rubber binders appear to have a decreasing rate of ablation with time of exposure (Fig. 9). The decrease in rate of ablation seems to be a function of char formation, char properties and thickness of the char formed. This type ablative material seems to offer some promise in nozzle throat applications.

3. Intumescent Ablative Materials

The U.S. Rubber Company has recently indicated that it appears feasible to develop an ablative nozzle throat that will maintain nearly constant dimensions during exposure to propellant flames by intumescense (expansion of char layer). The development of such a material would involve an extensive investigation of char properties.

J. PROCESSING OF ABLATIVE INSULATION MATERIALS

The primary factors considered in the processing and application of ablative insulation material are:

1. Time and cost of operations involved.
2. Effect of processing variables on material performance.
3. Inspection and quality assurance.

The processing methods generally used in the application of internal insulation materials are:

1. Hand lay-up.
2. Molding and adhesive bonding.
3. Casting
4. Spraying

The hand lay-up process has been used in the application of the epoxy-asbestos insulation for POLARIS motors. This method is time-consuming and expensive. However, the performance of the epoxy-asbestos insulation is not greatly affected by material impurities, catalyst levels and variation in curing conditions. Rubber insulations have also been applied by the hand lay-up process.

The cure and consequently the performance of rubber insulators may be affected considerably by impurities picked up on handling and by small variations in the concentration of catalyst and antioxidant. Variations in curing temperature and time may also affect their performance.

The use of molded rubber closures for the forward and aft end chamber insulation offers an advantage to the hand lay-up method in that a molded part can be pre-inspected before the bonding operation. A problem is introduced in adhesive bonding of rubber insulators. The use of molded rubber closures is also limited to a certain size chamber because of limitations in the size of molding equipment.

The application of internal insulation materials by casting and spraying offer some advantages to the hand lay-up and the molding-bonding procedure with regard to the time and the cost of the operations involved. Casting and spraying can also be used for application of the insulation in very large motors.

The effect of processing variations on the performance of rubber insulators has been studied to some extent by several firms. The performance of the nitrile-rubber asbestos system has in particular been improved by new processing techniques. It has been shown that the size and distribution of filler particles and the orientation of fiber reinforcement are important factors. The U.S. Rubber Company has, for example, demonstrated that one five-minute mixing cycle of asbestos (Plastibest 20) in styrene-butadiene rubber results in good flame performance. Repetition of the five minute mixing cycles up to twenty times shows that the rate of erosion for this system increases with time of mixing.

The processing of nozzle insulation involves, in general, compression molding and adhesive bonding. External insulation is generally applied by spraying.

TABLE I

CHEMICAL THERMODYNAMIC PROPERTIES OF FILLERS*

Filler	Formula	Form	Specific Gravity @ 20°C	M.P. °C	B.P. °C	ΔH Formation kcal/mole	Cp Cal/ degmole	ΔH Fusion kcal/mole	ΔH Vaporization kcal/mole
Graphite	C	amorphous	2.25	3500 sublimes	4200	0.0	2.066	—	—
Silicone**	Si	solid	2.42	1410-1420	2600	0.0	4.75	11.	—
Sulfur	S	rhombic	2.07	112.8	—	0.0	5.40	—	—
Sulfur	S	monoclinic	1.957	119.	444.6	0.071	5.65	0.293	—
Antimony oxide	Sb_2O_4	solid	5.2	656	1500 sublimes	-214	27.4	—	—
Boron Oxide	B_2O_3	solid	1.844	≈450	1250-1500	-302.0	14.88	5.27	77
Calcium Oxide	CaO	solid	3.37	2600	2850	-151.9	10.23	12.	—
Silicon dioxide	SiO_2	Quartz	2.653-2.660	1470	2230	-205.4	10.62	—	—
Silicon dioxide	SiO_2	tridymite	2.28-2.33	1670	2230	—	—	2.04	—
Titanium oxides	TiO_2	rutile	4.26	1640 d	—	-218.0	13.16	—	—
	TiO_2O_3	crystal	—	200	—	-367.	23.27	0.22	—
	TiO_3O_5	crystal	—	177	—	-584.	37.00	0.22	—
Zirconium Oxide	ZrO_2	crystal	5.47	2700	4300	-258.2	—	—	—
	$ZrO_2 \cdot 5H_2O$	amorphous	—	2677	—	-625.3	—	—	—

* Selected Values of Chemical Thermodynamic Properties, Circular 500, National Bureau of Standards.

** ΔH Sublimation, kcal/mole 171.698/250C

(Cont. Next Page)

TABLE I

CHEMICAL THERMODYNAMIC PROPERTIES OF FILLERS* (Continued)

Filler	Formula	Form	Specific Gravity @ 20°C	M.P. °C	B.P. °C	△H Formation kcal/mole	Cp Cal/degmole	△H Fusion kcal/mole	△H Vaporization kcal/mole
Zinc Oxides	ZnO	zincite	5.606	1975	—	-83.17	9.62	—	—
	$ZnO_2 2H_2O$	crystal	—	—	—	-207.9	—	—	—
	$Zn_3O_5 2H_2O$	crystal	—	—	—	-371.1	—	—	—
	$Zn_3O_5 3H_2O$	crystal	—	—	—	-437.7	—	—	—
	$3ZnO.2B_2O_3$	crystal	4.22	980	—		—	—	—
Silicon carbide	SiC	crystal	3.217	2600	sublimes	- 26.7	6.37	—	—
Titanium carbide	TiC	crystal	4.93	3140± 90	4300	- 54.	8.04	—	—
Zirconium carbide	ZrC	crystal	6.73	3540	5100	- 45.	—	—	—
Boric Acid	H_3BO_3	solid	1.435^{15}	185 d	-1 1/2H_2O 300	-260.2	19.61	—	—
	$K_2B_4O_7$	solid	—	—	—	-676.5	—	—	—
Calcium sulfate	$CaSO_4$	rhombic or monoclinic	2.96	mono 1450	trans. to rhombic 1193	-342.42	23.8	6.7	—
Magnesium sulfate	$MgSO_4$	crystal	2.66	1124 d	—	-305.5	23.01	3.5	—
Potassium Iodide	KI	solid	3.618^{15}	685	1324	- 78.31	13.16	—	—
Potassium oxalate	$K_2C_2O_4H_2O$	—	2.13	decomposes	—	-320.43	—	—	—
Oxalic acid	$H_2O_2O_4$	crystal	1.653	101;189 anhydrous	150 sublimes		—	—	—

TABLE II

TESTING PARAMETERS FOR OXYACETYLENE TORCH DEVICE, GT&R.

1.	Oxygen-acetylene ratio	1.029/1.00
2.	Total gas flow rate	72 scuf/hr
3.	Flame temperature	5600°F
4.	Test specimen dimensions	2 in. dia., 0.25 in. thick
5.	Specimen distance from torch tip	1 inch
6.	Specimen location	parallel position
7.	Torch oscillation onto specimen	60° angle, 10 cycles/min.

TABLE III

OXYACETYLENE FLAME TEST DATA FOR

INTERNAL INSULATION MATERIALS, GT&R(1)

Material	Exposure Time Sec.	Original Weight lb.	Weight Loss lb.	Specimen Thickness (inches) Original	Virgin	Char	Degraded	Thickness Loss Rate in/sec.	Temp Rise Backside of Specimen °F
Garlock 7765 (Garlock Packing Co.)	75	.0347	.0163	.26	.00	.00	.00	.0033	320
V-44 (General Tire & Rubber Company)	90	.0353	.0103	.25	.04	.34	.09	.0022	152
V-52 (General Tire & Rubber Company)	90							.0017	95
NC-1 (United States Rubber Co.)	90	.0344	.014	.24	.02	.63	.07	.0025	100
388-98 (Mare Island Naval Shipyard)	90	.0437	.0121	.26	.08	.27	.12	.0020	155
Q2-0103/10xy-115 (Dow Corning Corp.)	60	.0452	.0043	.26	.13	.00	.01	.0023	105
1126 (Nobell Research Lab)	90	.0410	.0225	.28	.00	.04	.13	.0031	50
M-707 (Goodyear Tire & Rubber Co.)	70	.0342	.0067	.27	.05	.04	.14	.0037	75
MX-4730 (Fiberite Corporation)	60	.030		.25	.13	.22	.06	.0028	125

(1) Oxygen-acetylene ratio, 1.029/1.0
Total gas flow rate, 72 cu ft/hr
Flame temp, 5600°F
Distance between torch tip and specimen, 1 in.

TABLE IV

OXYACETYLENE FLAME TEST DATA (RIME*)
FOR INTERNAL INSULATION MATERIALS

Material	Exposure Time, sec.	Char Rate Mil/sec.	Weight loss lb X 10^{-4}/sec	Temp. Rise, Backside of Specimen, °F
Garlock 7765, Garlock Packing Co.	90	1.85	1.12	320
V-44, General Tire & Rubber Co.	90	1.75	1.00	162
NC-1 (USR-3015) U.S. Rubber Co.	90	1.41	1.32	170
M-707 Goodyear Tire & Rubber Co.	90	1.90	0.91	84
SMR6-11 Stoner Rubber Co.	90	2.20	1.76	118
MX 4730, Fiberite Corporation	90	1.50	0.43	180

* Specimen size, 2 in. dia. X 1/4 in. thick
oxygen-acetylene ratio 1.2/1.0
Total gas flow rate, 6 X 10^{-3} lb/sec.
Heat flux, 72 BTU/ft^2 sec.
Flame temp. 5500°F
Distance between torch tip and specimen, 7 in.

TABLE V

PLASMATRON TEST[1] DATA FOR INTERNAL INSULATION MATERIALS

Material	Vendor	Heat Flux ($BTU/ft^2 sec$)	Mass Rate (lb/ft^2-sec)	Ablation Velocity (in/sec)	Char Depth (Mils)
V-44 (Nitrile)	General Tire & Rubber Company	730	.078	.0116	120
		830	.102	.0152	—
		960	.115	.0171	150
MX4730 (Silicone)	Fiberite	730	.046	.00663	50
		960	.090	.0129	50
SMR6-11 (Nitrile)	Stoner	730	.005	.00078	chars separated from specimens during cooling
		830	.011	.00171	
		960	.044	.00685	
SMR5025-3 (Nitrile)	Stoner	730	.094	.0124	50
		830	.102	.0135	50
		960	.139	.0183	50
SMR81-9 (Butyl)	Stoner	730	.079	.0106	65
		960	.107	.0144	60

(1) The Gianinini P-140 Plasmatron, Azusa
Subsonic, alumina-containing plasmajet
Helium used at flux levels of 730 and 960 BTU/ft^2-sec
Argon used at flux level of 830 BTU/ft^2-sec.

TABLE VI

RITE MOTOR DATA

Material			Firing Parameters		Weight Loss	Av Thickness Loss Rate	Av Char	Av Degraded Material	(Density) X
Designation	Vendor	Density g/cm^3	Duration sec.	Av Pc psig	g	in/sec	in.	in.	(Av TLR)
V-52	GT&R	1.318	92	355	---	.0067	.137	.033	.0088
M-707	Goodyr	1.187	85	341	750	.0078	.100	.043	.0093
V-44	GT&R	1.29	80	328	---	.0085	.158	.031	.0102
F-33	Narmco	1.47	86	322	601	.0084	.233	.040	.0124
9001	AGC, Azusa	1.29	75	325	701	.0097	.041	.021	.0116
1126	Nobell	1.19	88	344	936	.0105	---	---	.0121
3015	USR	1.27	78	340	---	.0106	.185	.029	.0135
SMR6-11	Stoner	1.227	82	400	889	.0129	.119	.051	.0158

TABLE VII

PERFORMANCE DATA FOR THE V-44, USR-3015 AND NOL-3098

MATERIALS IN ABL, ARC AND AGC SUB-SCALE TEST MOTORS

Test Motor	Av. TLR (Char Rate) Mil/sec		
	USR-3015	V-44	NOL-3098
ABL Peripheral Slab Motor	2.6	3.0	4.0
ARC Motor			
A3 First Stage Condition	3.7	3.2	3.3
A3 Second Stage Condition	2.2	1.65	---
AGC, RITE Motor			
A3 First Stage Condition	12.6	8.5	8.0

TABLE VIII

STATIC TEST FIRING RESULTS FOR FIRST STAGE POLARIS A2 INSULATION

Motor No.	Forward Head Insulation: Material	Forward Head Insulation: Thickness (in.)	Forward Head Insulation: Reported Results	Aft Head Insulation: Material	Aft Head Insulation: Thickness (in.)	Aft Head Insulation: Reported Results	Closure Insulation: Material	Closure Insulation: Thickness (in.)	Closure Insulation: Reported Results	Nozzle Boss Insulation: Material	Nozzle Boss Insulation: Thickness (in.)	Nozzle Boss Insulation: Reported Results
1PA2-7B	Asbestos-Epon 8	0.375	Charred and cracked	Asbestos-Epon 815	0.60 at knuckle 2.04 at boss	No effect 1" eroded at boss circumference	Asbestos-Epon 815	0.96 at central 1.03 at boss	.24 eroded away, eroded completely in two areas 6" x 2"	Pyrotex ring Asbestos 815	-	Charred, eroded away, charred
1PA2-2D	"	"	"	"	0.5 at knuckle 1.38 at boss	Charred, eroded away between 3-4 o'clock	"	1.44 at boss 1.76 at central	Charred and cracked	Asbestos 815	.050	Eroded away
1PA2-5D	"	"	"	"	0.5 at knuckle 1.34 at boss	Charred, eroded at 4 o'clock	"	1.12 at boss 1.44 at central	Not accessible	?		?
1PA2-6D	"	"	"	"	0.5 at knuckle 1.28 at boss	Charred, eroded 0.5 in. on the diameter	"	1.18 at boss 1.44 at central	Charred and cracked	Fiberite caps Pyrotex sleeve	-	Hole ½" x 4"
1PA2-7D	Asbestos MK-651	"	Charred and cracked	Asbestos MK-651	1-17 layers	2 top layers eroded away 5" from aft edge	Asbestos MK-651	3.00 at boss 1.5 at central	Charred and cracked	Astrolite sleeve Asbestos MK-651	.250	Eroded away
1PA2-8D	Asbestos Epon 8	"	Charred and cracked	Asbestos Epon 815	0.48 at knuckle 2.28 at boss	Charred and cracked, eroded 0.5" away	Asbestos Epon 815	3.00 at boss 1.5 at central	Not reported	Asbestos-Epon 815	.50	Not reported
1PA2-10D	.07" thick SMR-7 rubber asbestos	6 layers	Top layer within 36" dia eroded away	.070" thick SMR-7 rubber asbestos	12 layers	Top layer eroded 5-8" from aft edge	Aerorez 603 Asbestos 0.70" 0.21" SMR-7 rubber Aerorez 603-asbestos 0.70" SMR-7 rubber asbestos in central area	1.13" at boss	No effect 2 layers of rubber-asbestos eroded away	Astrolite sleeve Aerorez 603-asbestos	0.48	Little evidence of erosion not reported
1PA2-12	Asbestos-MK-651	0.250	Blackened but not charred	Asbestos MK-651	1-11 layers 1/8"	Partially eroded in two areas	Asbestos MK-651	2.12 at boss 0.36 at central	1st layer charred and cracked no effect	Astrolite cap Asbestos-MK-651	0.48	Charred, eroded away to 3/4" from fwd face of caps
1PA2-25	Asbestos-MK-651	0.250	No effect	Asbestos-MK-651	1-11 layers	1st layer partially eroded away	Asbestos-MK-651	2.20 at boss .375 at central	4 layers eroded between 30-35" dia.	Astrolite cap Asbestos-MK-651	4-6 layers	Eroded away

TABLE IX

THICKNESS LOSS RATE vs STATION

OF V-44 IN SECOND STAGE POLARIS A3 AFT CLOSURE

SECTION

Station	0°	45°	60°	75°	90°	105°	120°	135°
35	0	0	0	.0004	.0015	0	0	0
34	0	0	0	.0008	.0011	0	0	0
33	.0002	0	0	.0011	.0010	0	0	0
32	.0013	0	0	.0010	.0008	.0017	0	0
31	.0017	0	.0004	.0015	.0012	.0021	0	0
30	.0027	0	.0012	.0033	.0016	.0022	.0004	0
29	.0030	.0006	.0026	.0022	.0015	.0017	.0004	0
28	.0037	.0010	.0025	.0024	.0018	.0024	.0014	0
27	.0035	.0019	.0037	.0035	.0019	.0027	.0033	.0005
26	.0040	.0017	.0055	.0037	.0030	.0022	.0045	.0009
25	.0058	.0037	.0066	.0039	.0042	.0033	.0051	.0021
24	.0069	.0035	.0063	.0045	.0050	.0035	.0053	.0023
23	.0078	.0041	.0065	.0047	.0053	.0029	.0055	.0033
22	.0078	.0052	.0067	.0053	.0069	.0024	.0059	.0042
21	Nozzle Area	.0050	.0080	.0057	Nozzle Area	.0083	.0066	.0043
20	Nozzle Area	.0064	.0089	.0079	Nozzle Area	.0097	.0063	.0048
19	Nozzle Area	.0058	.0074	Nozzle Area	Nozzle Area	Nozzle Area	.0054	.0052
18	Nozzle Area	.0054	.0056	Nozzle Area	Nozzle Area	Nozzle Area	.0050	.0051

TABLE IX - continued

	SECTION							
Station	0°	45°	60°	75°	90°	105°	120°	135°
17	Nozzle Area	.0051	.0037	Nozzle Area	Nozzle Area	Nozzle Area	.0041	.0065
16	Nozzle Area	.0051	.0032	Nozzle Area	Nozzle Area	Nozzle Area	Nozzle Area	.0061
15	Nozzle Area	.0044	Nozzle Area	Nozzle Area	Nozzle Area	Nozzle Area	Nozzle Area	.0054
14	Nozzle Area	.0038	Nozzle Area	Nozzle Area	Nozzle Area	Nozzle Area	Nozzle Area	.0045
13	Nozzle Area	.0033	Nozzle Area	Nozzle Area	Nozzle Area	Nozzle Area	Nozzle Area	.0043
12	Nozzle Area	.0037	Nozzle Area	Nozzle Area	Nozzle Area	Nozzle Area	Nozzle Area	.0050
11	Nozzle Area	.0040	Nozzle Area	Nozzle Area	Nozzle Area	Nozzle Area	Nozzle Area	.0045
10	Nozzle Area	.0040	Nozzle Area	Nozzle Area	Nozzle Area	Nozzle Area	Nozzle Area	.0043
9	Nozzle Area	.0033	.0066	Nozzle Area	Nozzle Area	Nozzle Area	.0049	.0040
8	Nozzle Area	.0028	.0060	.0044	Nozzle Area	Nozzle Area	.0051	.0050
7	Nozzle Area	.0033	.0054	.0052	.0032	.0044	.0044	.0058
6	.0049	.0039	.0041	.0044	.0049	.0030	.0043	.0054
5	.0019	.0035	.0042	.0037	.0032	.0028	.0040	.0053
4	.0023	.0038	.0039	.0032	.0026	.0034	.0044	.0058
3	.0037	.0048	.0038	.0032	.0016	.0049	.0049	.0066

TABLE X

THICKNESS LOSS RATE vs STATION OF V-44

IN SECOND STAGE POLARIS A3 AFT CLOSURE

Station No.	90°	105°	120°	60°	135°	45°
0	----	----	----	----	----	----
1	.0022	.0025	.0025	.0025	.0012	.0012
2	.0023	.0023	.0024	.0024	.0012	.0012
3	.0066	.0055	.0064	.0064	.0066	.0066
4	.0047	.0050	.0062	.0043	.0050	.0042
5	.0067	.0022	.0088	.0034	.0087	.0063
6	Nozzle Area	Nozzle Area	.0056	.0056	.0091	.0050
7	" "	" "	Nozzle Area	Nozzle Area	.0099	.0031
8	" "	" "	" "	" "	.0061	.0028
9	" "	" "	" "	" "	.0063	.0035
10	" "	" "	" "	" "	.0052	.0052
11	" "	" "	" "	" "	.0057	.0057
12	" "	" "	" "	" "	.0061	.0051
13	" "	" "	" "	" "	.0067	.0079
14	" "	" "	" "	" "	.0078	.0093
15	" "	" "	" "	" "	.0076	.0097
16	" "	" "	" "	" "	.0086	.0112
17	" "	" "	" "	" "	.0101	.0110
18	" "	" "	.0131	.0085	.0108	.0123
19	" "	" "	.0114	.0059	.0113	.0122
20	" "	" "	.0095	.0060	.0102	.0121
21	" "	" "	.0105	.0038	.0094	.0107
22	" "	.0059	.0089	.0038	.0088	.0102
23	.0078	.0032	.0065	.0045	.0081	.0098
24	.0069	.0010	.0043	.0043	.0085	.0098
25	.0060	.0016	.0033	.0033	.0118	.0118
26	.0060	.0011	.0029	.0029	.0125	.0125
27	.0058	.0012	.0028	.0028	.0127	.0127
28	.0078	.0010	.0058	.0058	.0130	.0130
29	.0057	.0018	.0056	.0056	.0113	.0113
30	.0050	.0020	.0039	.0039	.0082	.0082
31	.0047	.0014	.0036	.0036	.0082	.0082
32	.0043	.0020	.0032	.0032	.0077	.0077
33	.0029	.0017	.0027	.0027	.0039	.0039
34	.0022	.0012	.0021	.0021	.0026	.0026
35	.0018	.0013	.0014	.0014	.0029	.0029

Average TLR (Thickness Loss Rate) .0059

TABLE XI

THICKNESS LOSS RATE vs STATION OF V-44
IN FIRST STAGE POLARIS A3 AFT CLOSURE

Station	Section: Across Nozzle	Section: Between Nozzles	Station	Section: Across Nozzle	Section: Between Nozzles
1.		.0078	24.	Nozzle Area	.027
2.	.008	.0074	25.	.021	.0274
3.	.0093	.0100	26.	.021	.0224
4.	.0116	.0145	27.	.019	.0191
5.	.0139	.0173	28.	.018	.0212
6.	Nozzle Area	.0176	29.	.019	.0234
7.	" "	.0169	30.	.018	.030
8.	" "	.0161	31.	.020	.0297
9.	" "	.0171	32.	.019	.0312
10.	" "	.0190	33.	.016	.0266
11.	" "	.0216	34.	.0105	.0184
12.	" "	.0270	35.	.0103	.0122
13.	" "	.0263	36.	.0089	.0064
14.	" "	.0259	37.	.0097	.0106
15.	" "	.0275	38.	———	.0112
16.	" "	.0295	39.	———	.0091
17.	" "	.0325	43.	———	.005
18.	" "	.0312	44.	———	.0044
19.	" "	.0312	46.	———	.0037
20.	" "	.0306	47.	———	.0025
21.	" "	.0294			
22.	" "	.0264			
23.	" "	.0245	Average Thickness Loss Rate		.0183

NOTE: Distance between stations - one inch

TABLE XII

THICKNESS LOSS RATE vs STATION OF V-44 IN SECOND STAGE MINUTEMAN AFT CLOSURE, ENGINE 44 FW-45 MOD 2 AND MOD 2X

Section	Station	TLR/in./sec. Mod. 2	TLR/in./sec. Mod 2X
Through 0°	15	.000	.006
"	14	.003	.011
"	13	.008	.015
"	12	.017	.022
"	11	.032	.038
"	10	Nozzle port	Nozzle port
"	9	" "	" "
"	8	" "	" "
"	7	" "	" "
"	6	" "	" "
"	5	" "	" "
"	4	.020	.024
"	3	.011	.006
"	2	.008	.007
"	1	.009	.007
"	0	.013	.007
through 45°	1	.010	.007
"	2	.008	.007
"	3	.007	.006
"	4	.008	.004
"	5	.009	.003
"	6	.011	.005
"	7	.013	.008
"	8	.020	.012
"	9	.033	.018
"	10	.042	.037
"	11	.040	.040
"	12	.043	.045
"	13	.047	.047
"	14	.038	.030
"	15	.018	.016
Average		0.019	0.0178

TABLE XIII

PHYSICAL AND MECHANICAL PROPERTIES* OF INTERNAL INSULATION MATERIALS

Material	Density (g/cc)	Tensile Strength at 77°F (psi)	Elongation at 77°F (%)	Shore A Hardness	Thermal Conductivity 250°F (BTU in/°F hr ft²)	Specific Heat 50°F (BTU/lb)
Garlock 7765 Garlock Packing Co.	1.24	3430	480	66	1.76	0.45
V-52 General Tire & Rubber Co.	1.33	1700	100	84	----	----
V-44 General Tire & Rubber Co.	1.29	1700	100	88	1.59	0.41
M-707 Goodyear Tire & Rubber Co.	1.19	900	375	97	----	----
NC-1(3015) U.S. Rubber Co.	1.26	3000	15	--	----	----
388-58, Mare Island Naval Shipyard	1.43	840	60	79	----	----

* Vendor Data

TABLE XIV

PLASMATRON TEST DATA* FOR

EXTERNAL INSULATION MATERIALS

Material	Density (lb/ft^3)	Argon Stagnation Enthalpy (BTU/lb)	Cold-wall Heat Flux (BTU/ft^2-sec)	Brightness Temperature (°F)	Mass Rate (lb/ft^2-sec)
Avcoat I	70.0	248	7		0.00015
		438	33		0.00182
		867	78	1930	0.02330
Dynel-Acrylic	66.0	248	7		0.00034
		438	33	1600	0.00327
		867	78	1663	0.01710
Thermolag 500	92.5	248	7		0.0002
		438	33	1480	0.0054
		867	78	1663	0.0110
Aerocoat I	69.2	248	7		0.00048
		438	33	1940	0.00357
		867	78	2020	0.02820
Dynatherm D-65	63.3	248	7		0.00704
		438	33		0.01090
		867	78	1730	0.01530
DC-651	76.6	248	7	<1400	0.000023
		438	33	<1400	0.000054
		867	78	1730	0.00129

*The Giannini P-140 Plasmatron, argon gas

TABLE XV

THERMAL PROPERTIES OF EXTERNAL INSULATION MATERIALS

Materials	Thermal Conductivity		Specific Heat		Coefficient of Thermal Expansion	
	MERM Temp (°F)	BTU in/°F hr ft²	Temp (°F)	BTU/lb °F	Temp Range (°F)	in/in/°F
Avcoat I	130	1.33	-15	0.54	77-350	9.5×10^{-5}
	230	1.38	50	0.55		
	250	1.44				
Thermolag	150	1.42	-15	0.38	90-400	3.98×10^{-5}
	200	1.49	50	0.38		
	250	1.59				
Dynatherm D-65	150	0.63	-15	0.45	128-200	7.10×10^{-5}
	200	0.77				
	250	0.79				
Aerocoat II	150	1.32	-15	0.40	90-200	7.45×10^{-5}
	200	1.37	50	0.40		
	250	1.36				
DC-651	150	1.56	-15	0.49	77-500	1.12×10^{-4}
	200	1.56	70	0.52		
	250	1.56	140	0.54		
Armstrong 2755 Cork	130	0.73	-15	0.39	----	----
	150	0.75	50	0.41		
	180	0.76				
	230	0.79				

TABLE XVI

PHYSICAL AND MECHANICAL PROPERTIES OF EXTERNAL INSULATION MATERIALS

Material	Density (lb/ft^3 g/cc)	Tensile Strength (psi)	Mod of Elast. (psi X 10^3)	Water Absorption Immersion (hrs)	Water Absorption Weight Change(%)
Avcoat I	70.0	6197	261.0	8	+0.67
Thermolag 500	92.5	747	166.0	8	-4.52
Dynatherm D-65	63.3	___	___	8	-6.72
Aerocoat II	66.4	1735	80.0	8	+1.6
D6-651	76.6	1920	0.582	8	+0.13
Armstrong 2755 Cork	30.0	255	6.2	-	___

TABLE XVII

OXYACETYLENE FLAME TEST DATA* FOR NOZZLE INSULATION MATERIALS

Material	Exposure Time Sec.	Original Weight lb.	Weight Loss lb.	Specimen Thickness (inches) Original	Virgin	Char	Degraded	Mass Loss Rate lb/sec	Thickness Loss Rate in/sec	Temp. Rise Backside of Specimen °F
Fiberite MX-3586, Nylon, graphite-phenolic resin	30	.0825	.0097	.57	.28	.36	.00	.00032	.0096	0
	60	.0836	.0166	.57	.25	.39	.00	.00027	.0053	0
	77	.0816	.0194	.50	.22	.41	.00	.00025	.0036	25
Fiberite MX-3596-67, Pyrographite coated graphite cloth-phenolic resin	20	.0410	.0045	.27	.00	.31	.00	.00022	.0135	320
	24	.0408	.0053	.27	.00	.31	.00	.00022	.0112	320
U.S. Polymeric (FM 5014) Graphite cloth phenolic resin	30	.0427	.0053	.27	.13	.17	.00	.00017	.0046	330
	41	.0427	.0063	.27	.00	.30	.00	.00015	.0066	330
	28	.0426	.0047	.27	.00	.28	.00	.00016	.0096	325
Fiberite MX-2625, Silica fabric-phenolic resin	41	.0498	.0062	.26	.03	.22	.00	.00015	.0056	190
	47	.0480	.0068	.25	.00	.23	.00	.00014	.0053	325
Fiberite MX-2646, Silica fabric-phenolic resin	60	.0509	.0079	.26	.00	.31	.00	.00013	.0043	310
	67	.0525	.0083	.26	.00	.25	.00	.00012	.0038	320
Coast Mfg. Supply (F-122) Quartz fiber-phenolic resin	30	.0428	.0060	.25	.11	.15	.02	.00020	.0046	55
	62	.0428	.0093	.25	.00	.28	.00	.00015	.0040	330
Coast Mfg. Co. (F-122-6) Refrasil-phenolic resin	30	.0531	.0050	.29	.11	.15	.02	.00019	.0060	65
	57	.0520	.0105	.29	.00	.23	.00	.00018	.0050	325
	56	.0522	.0097	.29	.00	.25	.00	.00017	.0051	320

* GT&R Test Facility

TABLE XVIII

PLASMATRON TEST DATA FOR NOZZLE INSULATION MATERIALS*

Material	Heat Flux BTU/ft^2-sec.	Mass Rate lb/ft^{2}sec.	Char Depth mils
Fiberite MX 2630A (Graphite cloth-phenolic resin)	830 1340 1590	0.078 0.127 0.185	130 560 510
Fiberite MX 2630A-67 (Graphite cloth-phenolic resin)	815 1119 1360	0.099 0.157 0.175	300 500 500
U.S. Polymeric FM 5019 (Silica cloth-phenolic resin)	1119	0.208	200
Fiberite MX 2625 (Silica cloth-phenolic resin)	830 1340 1540	0.056 0.212 0.286	75 50 --
Fiberite MX 1344-67 (Quartz-phenolic resin)	815 1119 1360	0.080 0.175 0.263	50 50 50

* AGC-Azusa Test Facility

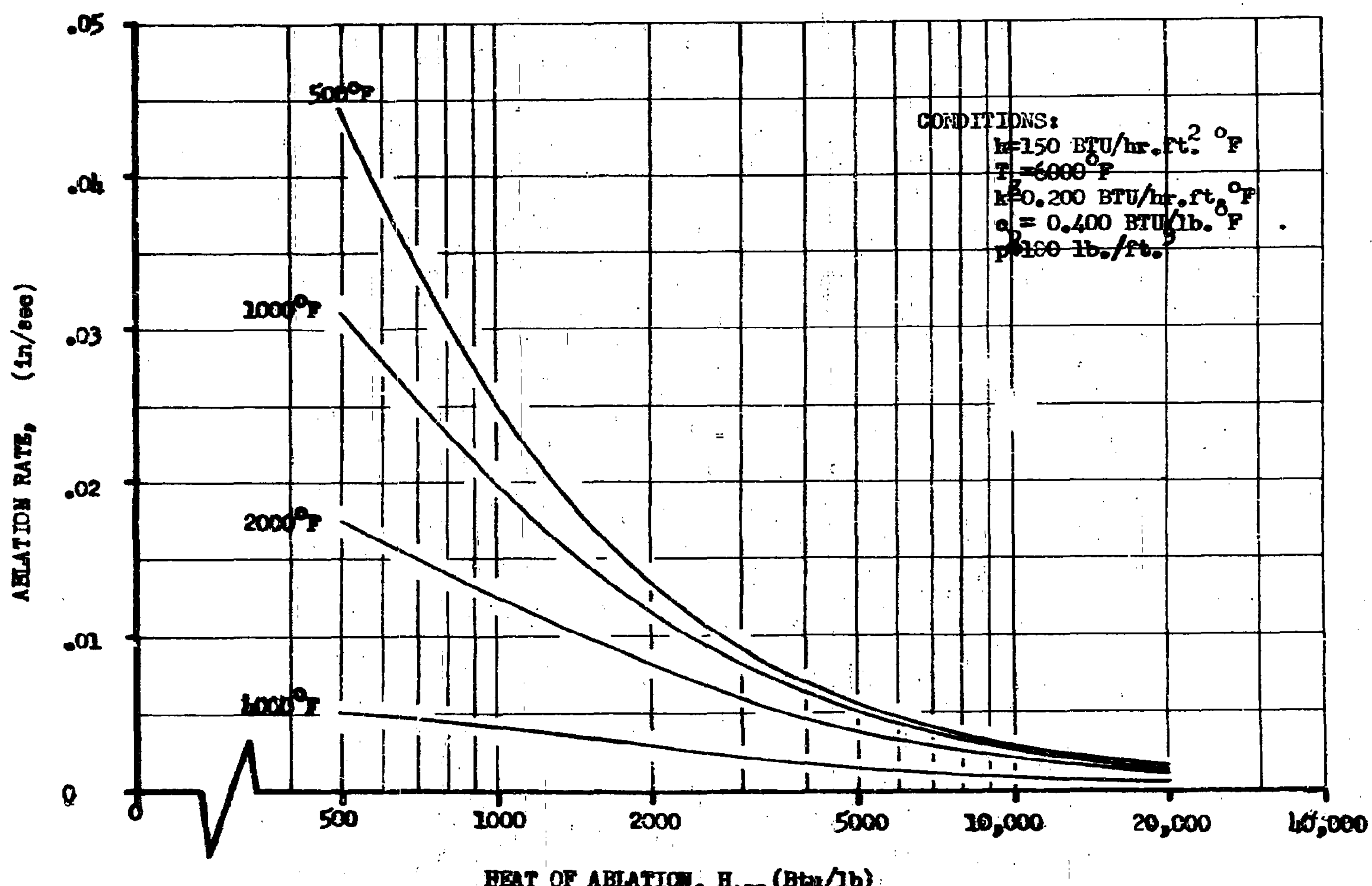
TABLE XIX

PLASMA JET TEST DATA FOR NOZZLE INSULATION MATERIALS*

Material	Heat Flux BTU/ft2sec.	Plasma Temp. °F	Plasma Enthalpy BTU/lb	Duration sec.	Plasma Gas	Weight Loss lb x 10^{-2}
Fiberite MX 4566 (Silica fiber-polyamide modified)	680	8000	6450	100	N_2	2.04
U. S. Polymeric FM 5019 (Silica Cloth-phenolic w/filler)	680	8000	6450	100	N_2	2.08
Fiberite MX 2646 (Silica cloth-polyamide modified)	680	8000	6450	100	N_2	2.99
Fiberite MX 2625 (Silica cloth-phenolic w/filler)	680	8000	6450	100	N_2	3.07
U.S. Polymeric FM 5014 WG (Graphite cloth-phenolic w/filler)	720	8300	6780	100	N_2	1.55
U.S. Polymeric XA 5-42-1 (Graphite cloth-phenyl silane w/filler 20% carbon fiber)	720	8300	6780	100	N_2	3.33
Fiberite MX 2630A (Graphite cloth-phenolic w/filler)	680	8000	6450	100	N_2	3.32
Fiberite MX 4551 (Graphite cloth-polyamide modified)	680	8000	6450	100	N_2	3.33
Fiberite MX-4925 (Carbon fiber-polyamide modified)	680	8000	6450	100	N_2	3.76

* AGC Sacramento Test Facility

FIGURE 1. Effect of Heat of Ablation on Ablation Rate For Various Ablation Temperatures



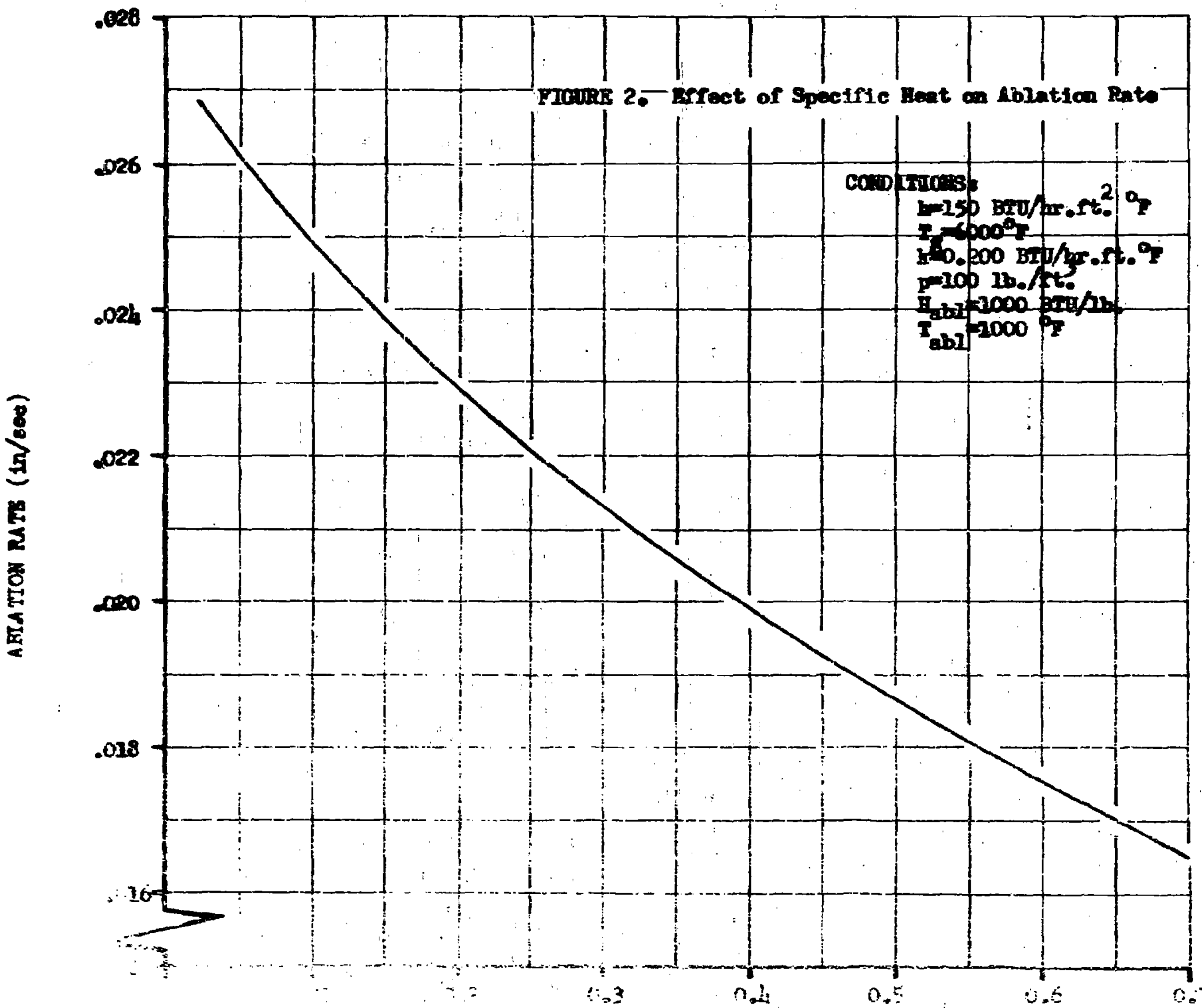


FIGURE 2. Effect of Specific Heat on Ablation Rate

FIGURE 3. Effect of Thermal Conductivity on Ablation Rate

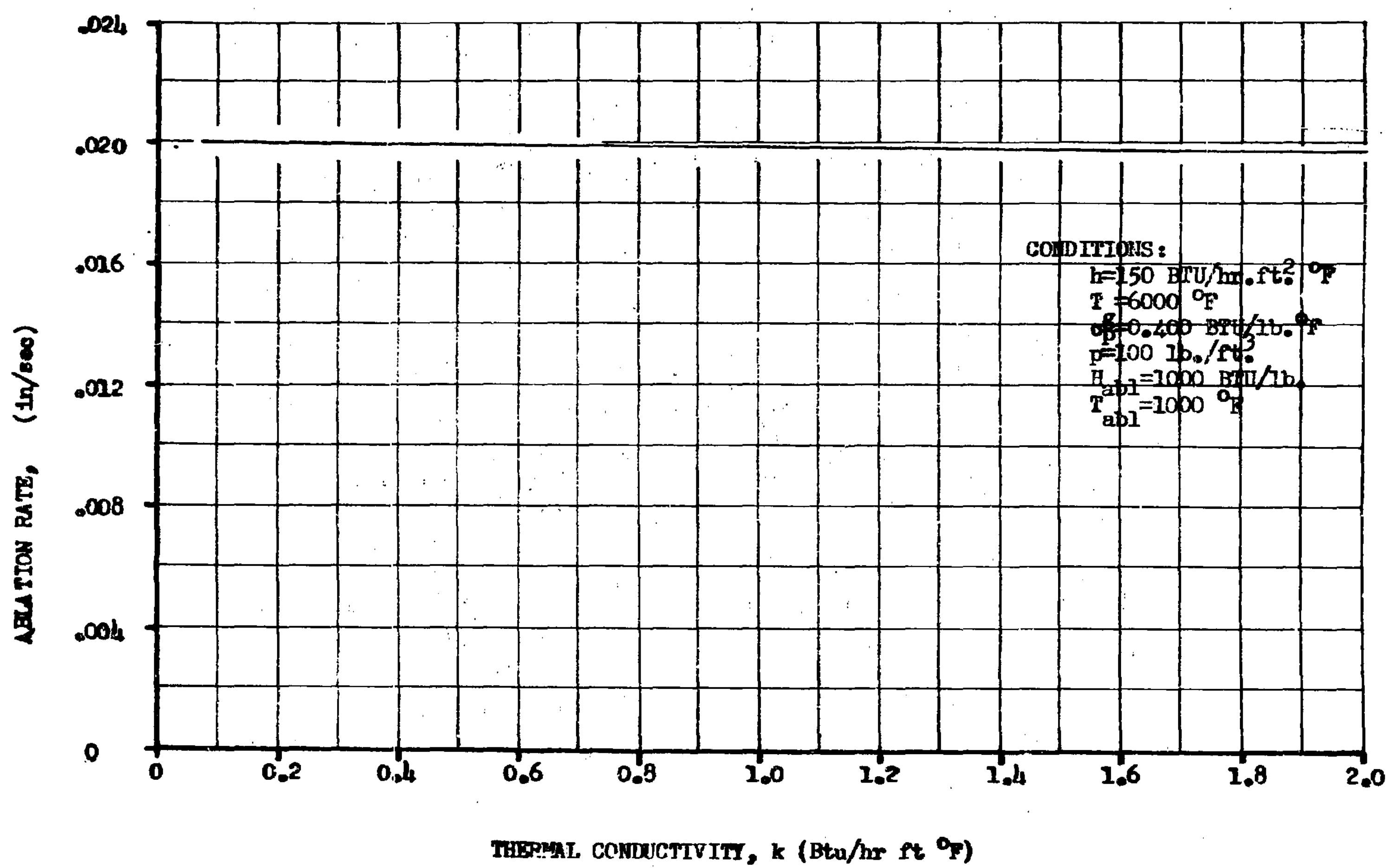


FIGURE 4. Solid Phase Temperature Distribution for Various Thermal Diffusivities

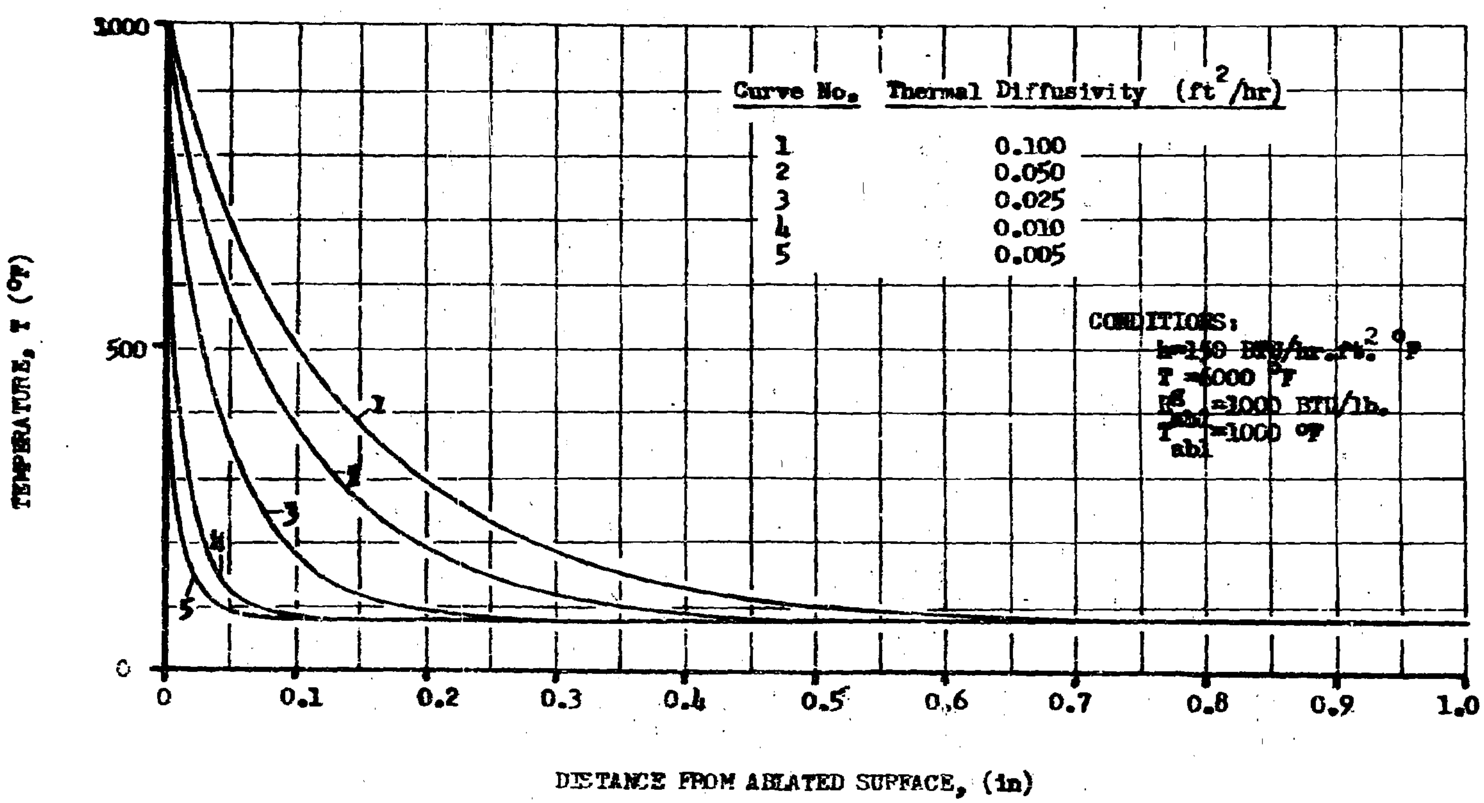


FIGURE 5. Percent of Total Heat Flux Transferred to Solid Phase as a Function of Specific Heat

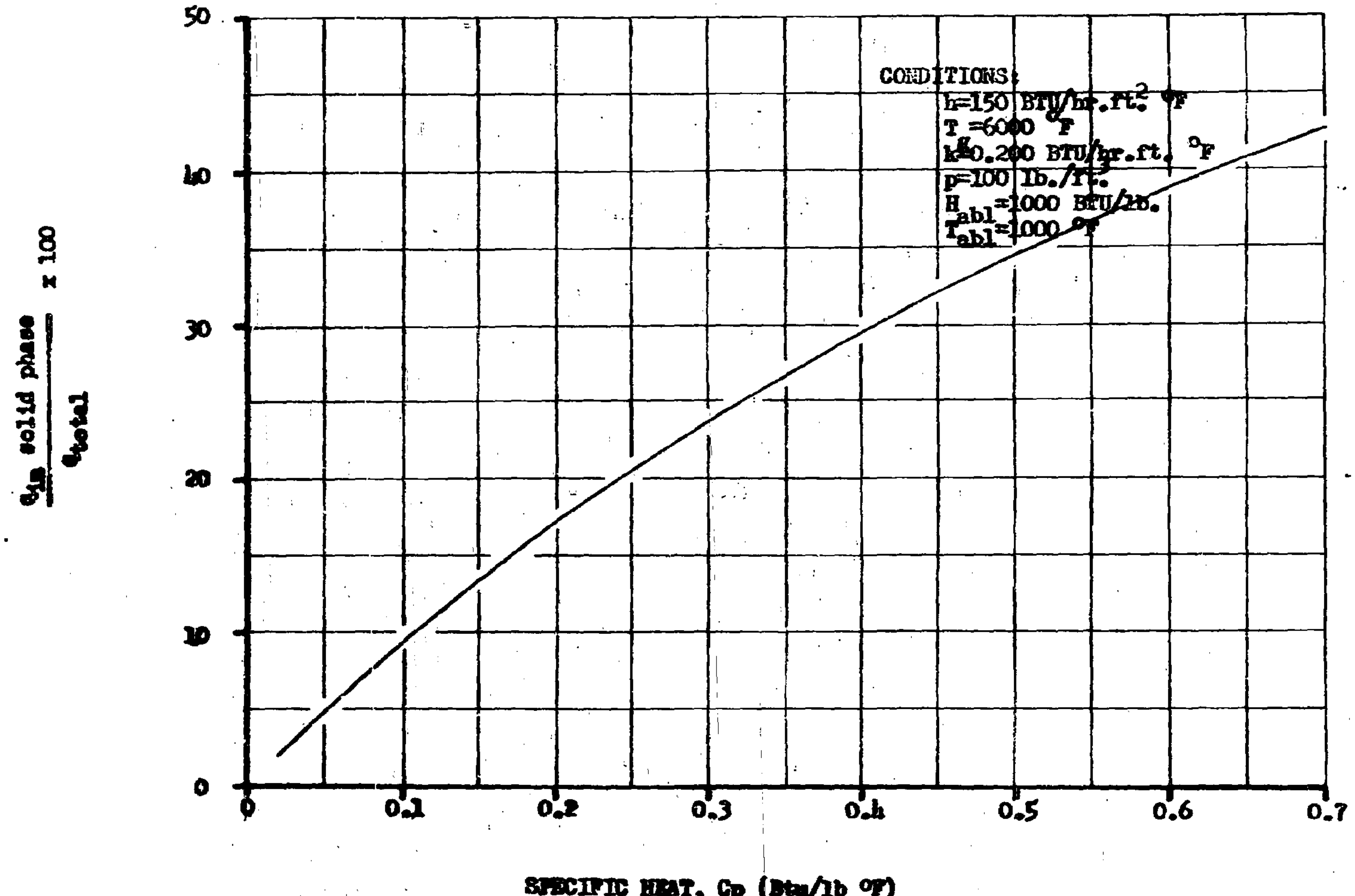
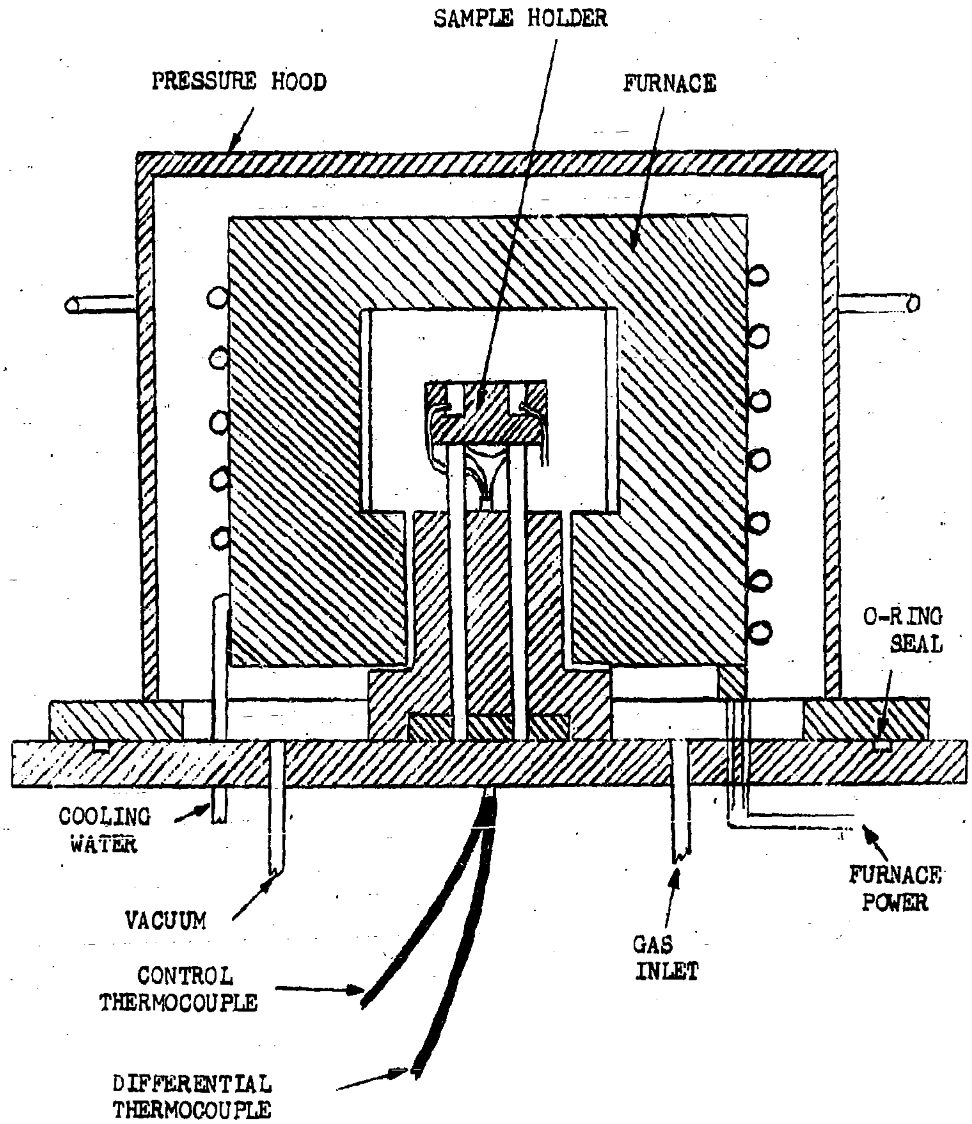


FIGURE 6

CROSS - SECTIONAL DIAGRAM OF
ATMOSPHERE FURNACE FOR DTA



Reference: WADC TR 59-136

FIGURE 7

THICKNESS LOSS RATE (TLR) AND DENSITY X TLR

OF INSULATION MATERIALS

IN THE RITE MOTOR

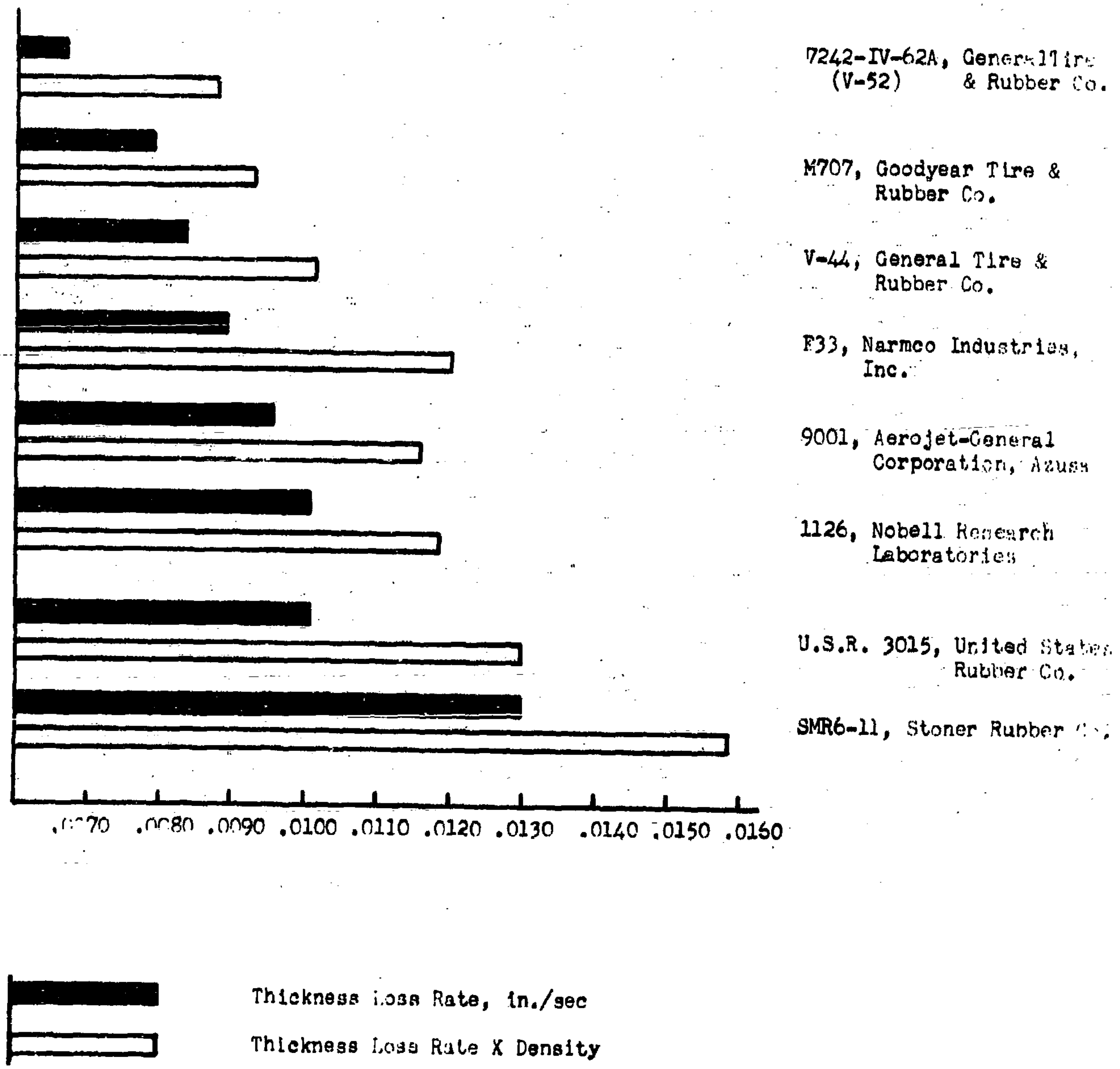


Figure 8

THICKNESS LOSS RATE VS. CHAMBER PRESSURE
OF V-44 IN RITE MOTOR TESTS

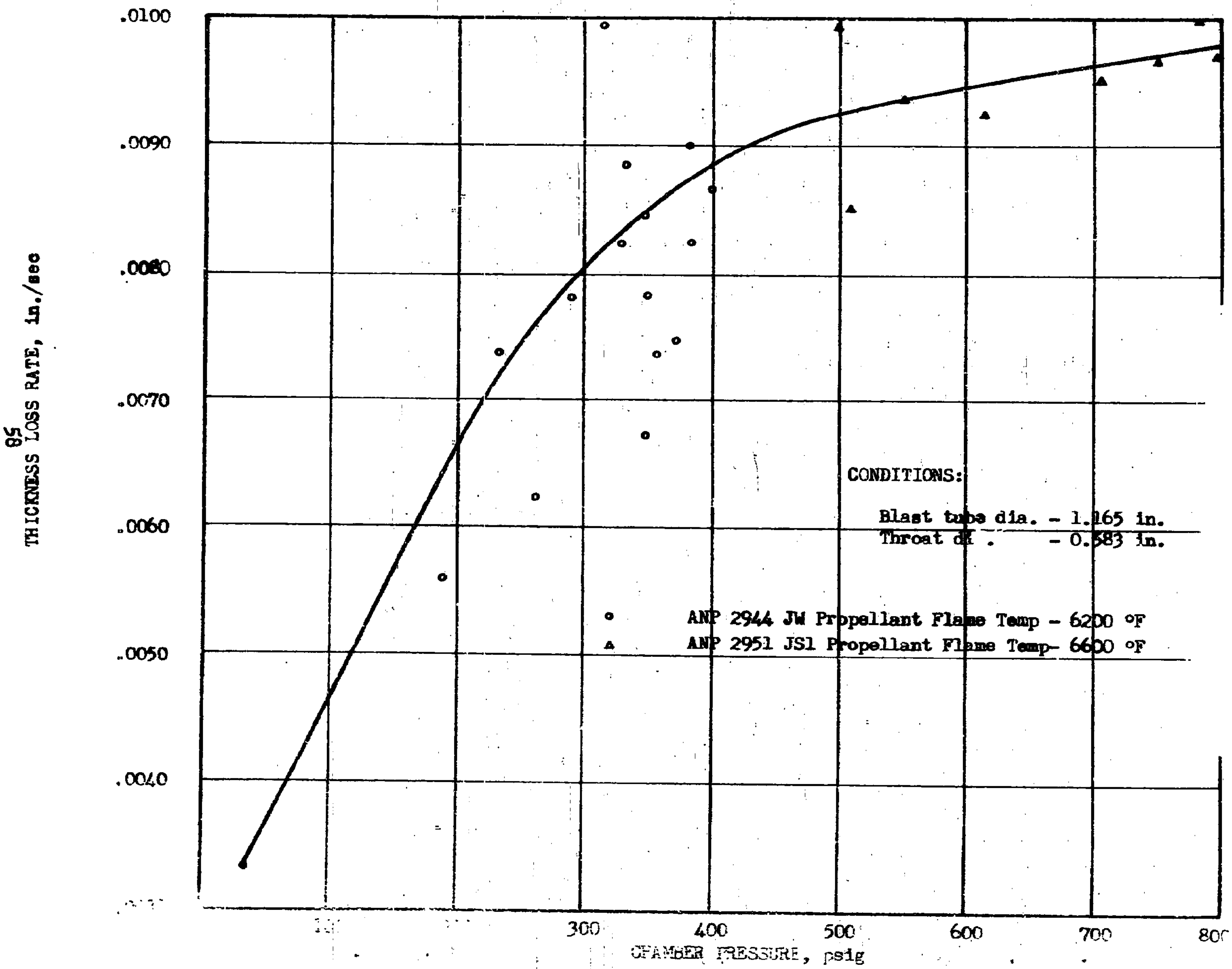


Figure 9

THICKNESS LOSS RATE (TLR) VS. TIME OF EXPOSURE FOR V-44 MATERIAL IN THE RITE MOTOR

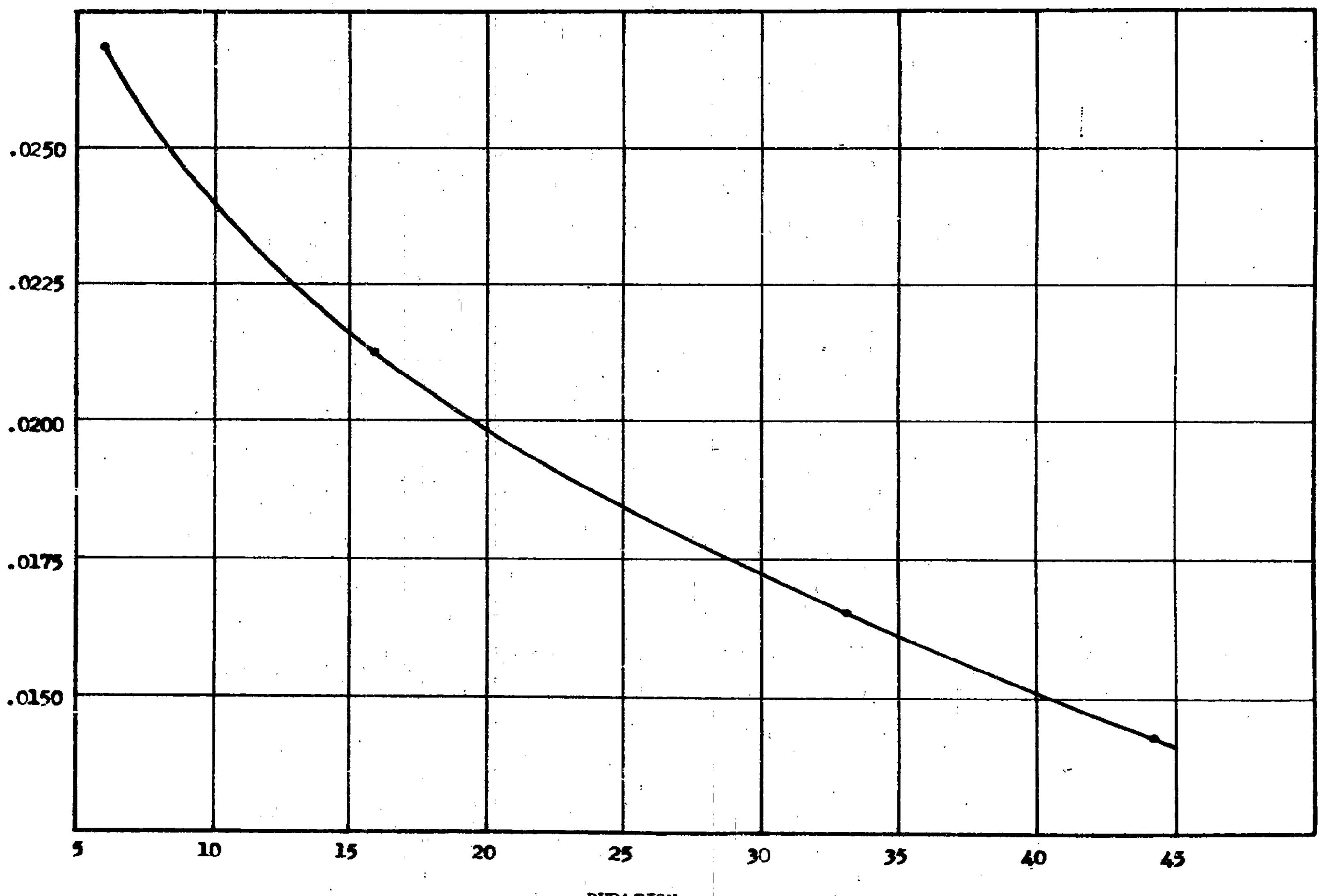
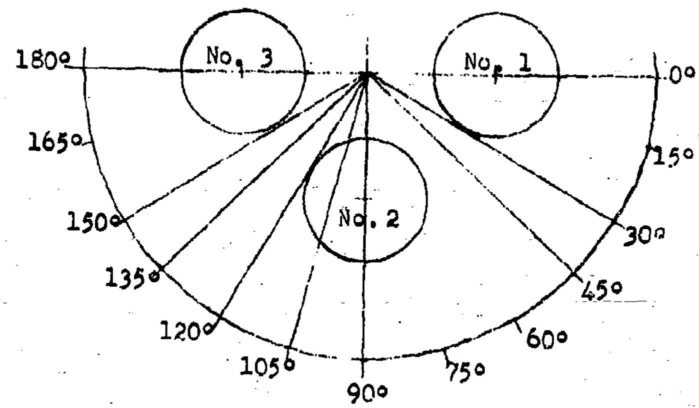


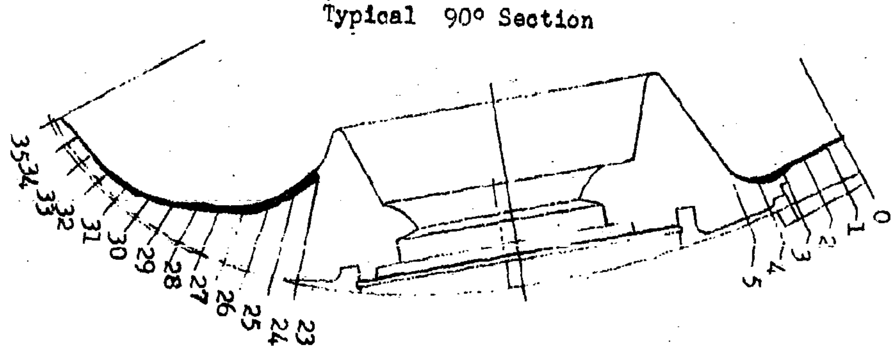
FIGURE 10

LOCATION AND TYPICAL VIEWS OF CROSS SECTIONED AREAS AND STATIONS USED IN REPORTING TLR (THICKNESS LOSS RATE) OF INSULATION MATERIALS FOR POLARIS AND MINUTEMAN AFT CLOSURES

View Looking Forward



Typical 90° Section



Typical 45° and 135° Section

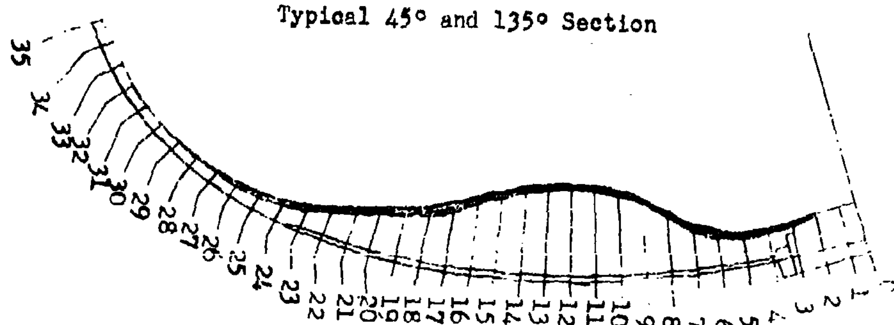
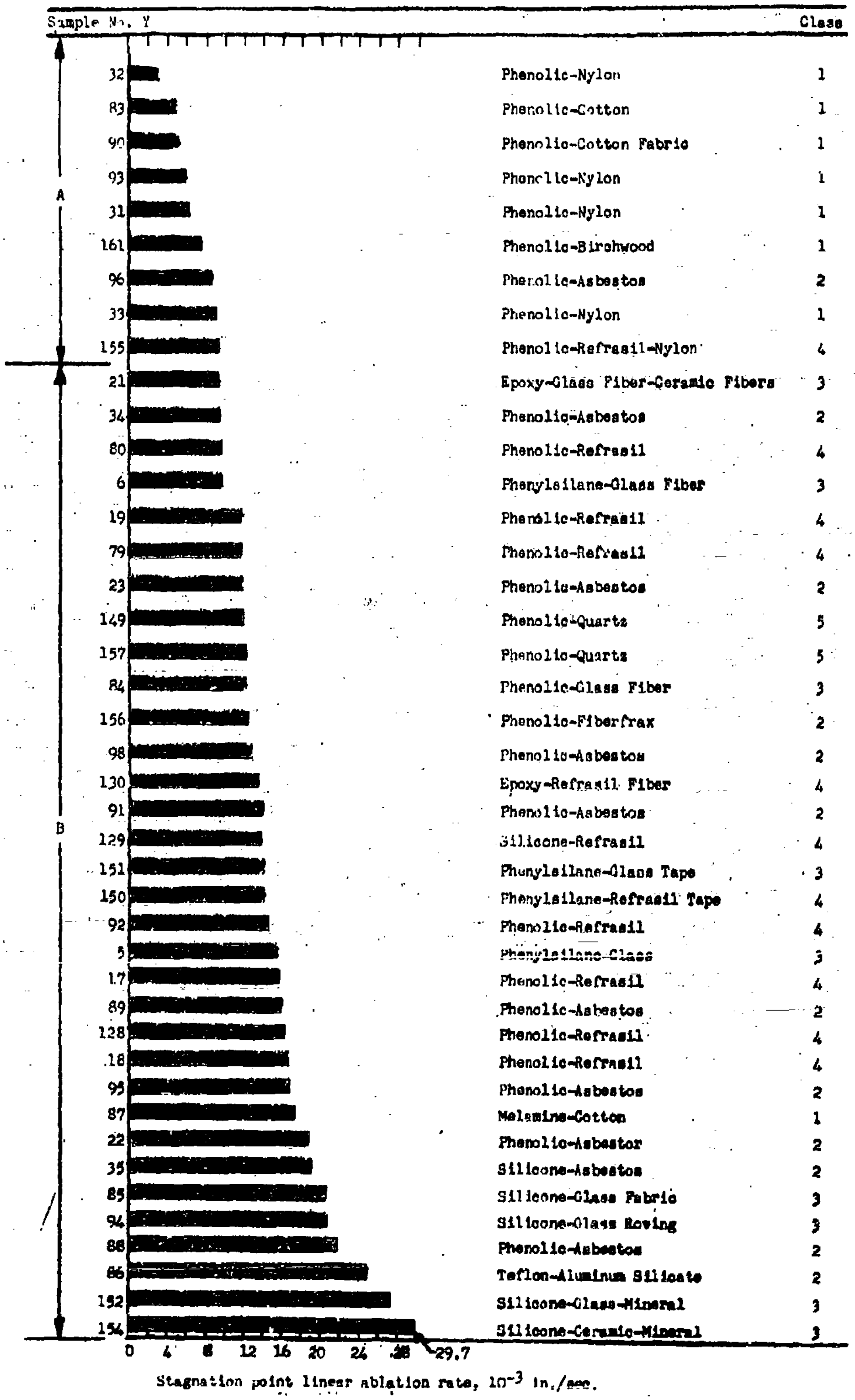


FIGURE 11

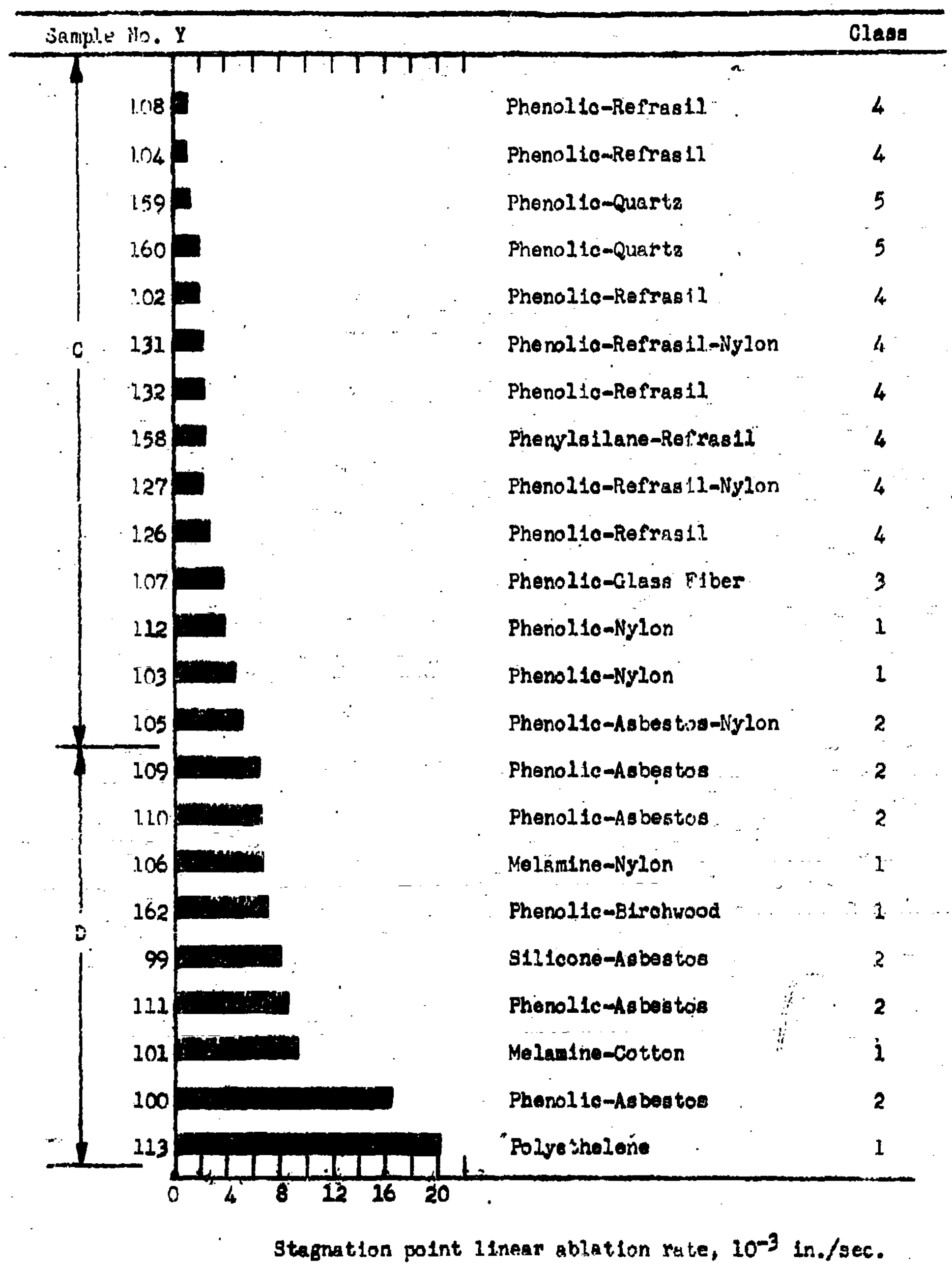
STAGNATION POINT LINEAR ABLATION RATES OF SAMPLES
EXPOSED TO HIGH HEAT FLUX (1950 BTU/ft^2-sec)



Reference: WADD TR 60-101

FIGURE 12

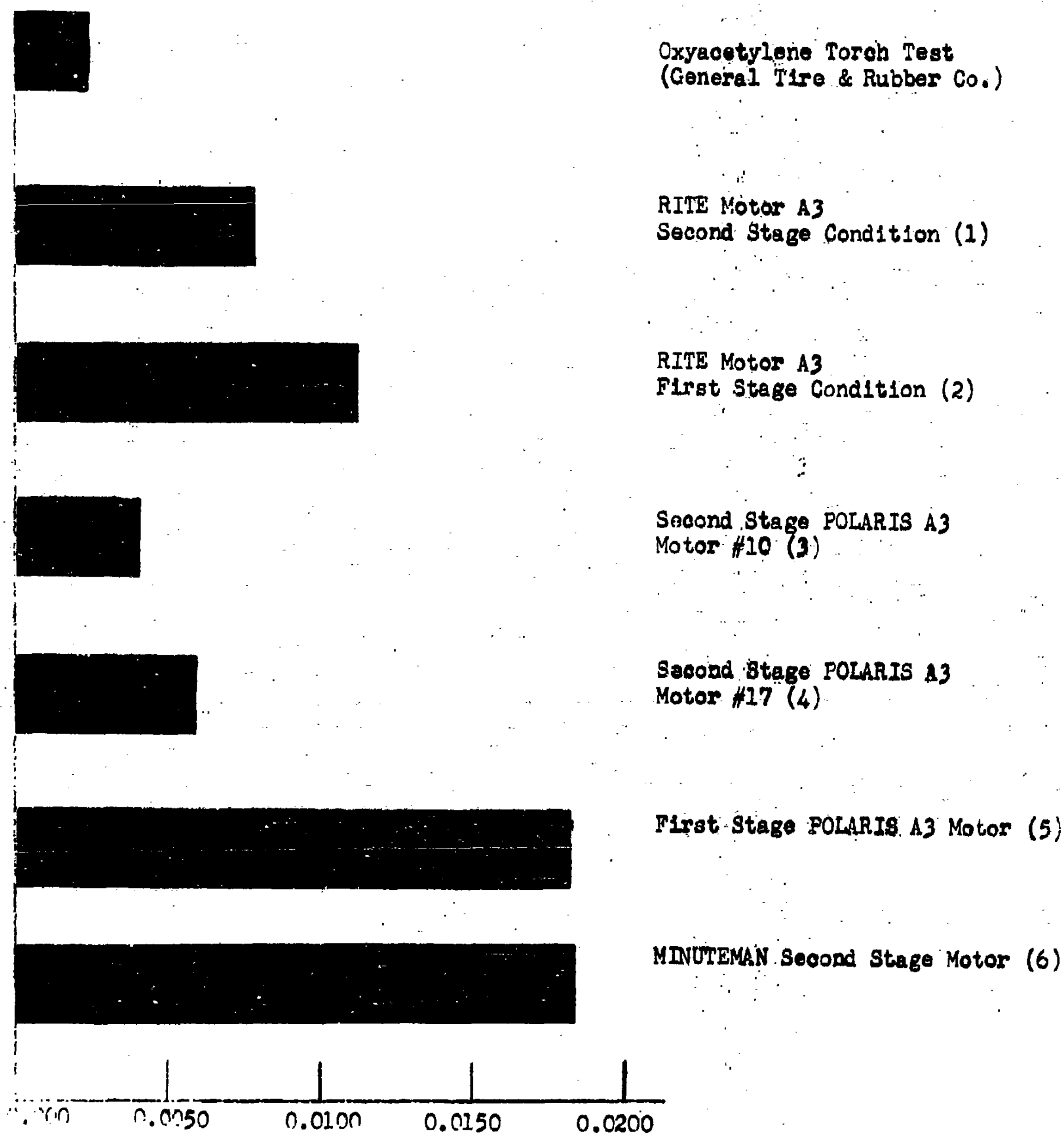
STAGNATION POINT LINEAR ABLATION RATES OF SAMPLES EXPOSED TO LOW HEAT FLUX (600 BTU/ft^2-sec)



Reference: WADD TR 60-101

FIGURE 13

Average TLR (Thickness Loss Rate) of V-44 in Oxyacetylene Torch Test, Rite Motor, First and Second Stage POLARIS A3 Motors, and Second Stage Minuteman Motor



TLR (Thickness Loss Rate) in/sec.

(1) Average of 10 specimens 1.165 tube diameter, 328 psig, 80 sec duration.

(2) Average of 3 specimens .839 tube diameter, 716 psig, 85 sec duration

(3) Motor #10, 235 psig, 85 sec duration.

(4) Motor #17, 250 psig, 68 sec duration.

(5) Motor #35, 703 psig, 74 sec duration.

(6) Mod 2 and Mod 2X.

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APPENDIX "A"

GLOSSARY OF TERMS

Ablation:	A surface degradation process involving decomposition and detachment of material.
Ablating Zone:	The ablating zone consists generally of a decomposing material layer and a protective char layer through which the decomposition products are emitted.
Char Layer:	A protective layer of carbon and other particles that remains as an integral part of the eroding material. The char layer may vary in composition relative to the surface of the protective layer.
Rate of Ablation:	Rate of thickness reduction of virgin (non-degraded) material.
Char Rate:	Rate of thickness reduction of virgin material (rate of ablation).
Rate of Erosion:	Rate of thickness reduction of charred material. The char layer is included as an integral part of the eroding material.
Heat of Ablation:	The heat energy dissipated through the thermochemical and thermophysical reactions involved in the ablation process.

Appendix "A" (Cont.)

Effective Heat of Ablation:

$$Q = \frac{Q_o \circ A}{w^\circ}$$

Where Q_o - Heat input Btu/ft^2sec as measured with cold wall water calorimeter.

A - Test specimen area - ft^2

w° - Weight loss with char layer included - lb/sec

Reference: RD-R161-211 Aerojet-General Corporation Structural Material Division, Azusa

Transpiration Cooling: Mass transfer cooling between the impinging particles (of propellant exhaust) and particles from the decomposing layer that transpires through the char layer.

Internal Insulation: The insulation items generally included in this term are the forward and aft chamber closures, boots and heads.

APPENDIX B

DESCRIPTION OF TEST DEVICES

I. DESCRIPTION OF TEST DEVICES

The following pages contain a description of test devices, their operating conditions, and test procedures used by various organizations for the evaluation of materials. Test equipment included in this report are as follows:

- Oxyacetylene Torch Test
- Oxy-kerosene Torch Test
- Gaseous Test Motors
- Plasma Jets
- Subscale Solid Rocket Test Motors

Equipment and organization is shown in Table I.

A. Oxyacetylene Torch Test Facilities

1. Atlantic Research Corporation

a. Appartus, (see Figure 1)

Torch Body - Airco Style - 800
Torch Tip - Airco Style-8, No-10, 1/8" Dia. Tip Opening
High Flow Mixer - Air Reduction Co., No. -811-0899
Acetylene and Oxygen Manifold and Tanks
Two-Stage Regulators) Metallizing Engineering Co.
Flowmeters)
Pressure Gauges
Torch Carriage - Air Cylinder Actuated
Air Cylinder - 5" Strike Double Action with Manual and Four-Way Solenoid Control, A. Schroder's Son Company
Micrometer Screw & Locks for Torch Positioning

APPENDIX B

Sample Holder Assembly
Photocell and Thermocouple
Rapid-Response Chart Recorder, Varian Associates, Inc.
Timing Clock, 100th of a Second
Iron-Constantan Thermocouples (24 Gauge) Soldered to 1" Dia., .009" Thick Metal Discs
Enclosed Test Chamber with High Speed Exhaust System

b. Test Procedure

Specimen thickness and weight are measured before the test. The specimen is placed on top of the metal disc of the thermocouple assembly in the specimen holder. Between the metal disc and sample is a thin contact film of conductive oil. A cover plate is placed over the sample holder. The thermocouple connections, jack and plug type, are made.

The torch tip is adjusted to 1.00 inch distant from specimen surface with micrometer screw. The torch is retracted to a standby position.

The torch is ignited and adjusted to a preset acetylene to oxygen ratio.

The torch is manually actuated to the test position.

The timer and recorder are turned on when the torch in the test position contacts a mocroswitch. The test is continued until the specimen is burned through. At the instant of burnthrough the photocell actuates a air cylinder, retracting the torch, stopping the timer and temperature recorder. This completes the test.

c. Test Conditions

Specimen Size 2.50"x2"x2" or 2.250" dia.

Torch Distance 1.00 inch

Angle of Impingement 90°

Oxygen/Acetylene Ratio 2.50

Total Gas Flow 300 cu. ft/hr.

Flame Temperature 5400°F

Flame Condition Highly oxidizing

Duration of Test Specimen burnthrough

d. Calculations

Initial and final weight ratio.

Initial thickness (inch)

Specific gravity

Total exposure time - 1 E. time to burnthrough

The temperature of the unexposed side of the sample during the total exposure time. (°F)

Erosion Index: mils/sec, $I_e = t_o + E\ bt$

Insulation Index: $I_i = E\ (400°F) + t_o$

Weight Ratio: $WR = W_f + W_o$

e. Where

t_o = Original thickness, inch

E (400) = Time of exposure for thermocouple to reach 400°F, sec.

Ebt = Time of exposure for specimen burnthrough

W_f = Final weight.

W_o = Original Weight.

2. Naval Ordnance Laboratory

a. Appartus, (see Figure 2)

Torch Tip, Victor No. 7
Water cooled specimen holder assembly.
Specimen positioning control mechanism.
Remote controlled solenoid actuated torch mount.
Fume removal system.
Instrumentation panel.
Control panel
Thermocouple, Chromal Alumal.
Oxygen and acetylene tanks and mixing manifold.
Pressure gauges, flow meters and regulators.
Chart recorder.
Timing clock.

b. Test Procedures

Insulation test specimen thickness and weight are measured before each test.

The specimen is secured to the watered cooled specimen holder and thermocouple connections are made.

The test specimen is positioned .750" from the torch tip with the positioning control mechanism. The torch is then retracted to a standby position by a pivot assembly.

The torch is then ignited and adjusted to a present oxygen/acetylene ratio.

The torch is actuated to the test position which starts the timer and recorder by means of a microswitch.

Visual and optical pyrometer observations are made during testing and any unusual effects noted.

The test is continued until the specimen is burned through. At the instant of burnthrough the solenoid retracts the torch to standby position, stopping the timer and temperature recorder. This completes the test.

c. Test Conditions

Specimen Size,	.250" x 2" x 2"
Torch Distance,	.750"
Angle of Impingement,	90°
Oxygen-Acetylene Ratio,	1.28
Gas Flow Rate,	253 scfh
Flame Temperature,	5540°F
Flame Condition,	Oxidizing
Duration of Test,	Specimen burnthrough

d. Calculations

Original thickness, mils

Exposure time for specimen back temperature to reach 392°F (200°C).

Total exposure time for specimen burnthrough, sec.

Index of Performance, 392°F + E (392°F) x ER

Erosion Rate, mils/sec, $t_o + E_{bt}$

e. Where

t_o = Original thickness, mils.

E (392°F) = Exposure time for specimen back temperature to reach 392°F, sec.

E_{bt} = Total exposure time for specimen burnthrough, sec.

f. Rating of Materials

Index of Performance (IP) is defined as the product of the erosion rate (i.e., original specimen thickness divided by the burnthrough time) and the average temperature gradient between room temperature and 200°C obtained on the cool face of the specimen (i.e., 200°C divided by the time required to reach 200°C). Thus, the I.P. is a composite measure of the specimen. A low IP is obviously desirable and the materials are ranked by this criterion.

Erosion Rate (ER) original specimen thickness divided by the burnthrough time.

3. Allegheny Ballistics Laboratory

a. Apparatus

Torch - Airco Welding, Style 800

Tip - Airco No. 6

Flow Meters - Matheson No. 206

Temperature Indicator - Tempilac paint directly on sample back.

b. Test Conditions

Specimen Size	.375 x 3" x 3"
Torch Distance	.500"
Angle of Impingement	90°
Acetylene, Oxygen Ratio	0.87
Gas Flow Rate	53 scfh
Flame Temperature	5110°F
Flame Condition	Reducing

c. Calculations

Original thickness, in.

Exposure time for specimen back temperature to reach 200°F, sec.

Total exposure time for specimen burnthrough, sec.

Char depth, in. $(t_o - t_v) + 2$
or
Erosion depth, in $(t_o - t_f) + 2$

d. Where

t_o = Original thickness, in.

t_v = Virgin layer thickness, in.

t_f = Final thickness, in.

E (200°F) = Exposure time for specimen back temperature to 200°F, sec.

E_{bt} = Total exposure time for specimen burnthrough, sec.

4. U. S. Rubber Corporation

a. Apparatus

Torch Body	Airco, Style 800
Torch Tip	No. 10
High Flow Mixer	Air Reduction Co. No. 811-0899
Torch Adapter	Air Reduction Co. No. 811-0390
Thermocouple	Iron-Constanten
Recorder	L&N Recording Potentiometer

The torch tip is equipped with a water cooled jacket.

The acetylene tanks are tapped through a manifold and two regulators, the first a two stage, and the second a single stage.

The gas flows are measured with Brooks rotometers and passed through check valves and a quick shut-off valve before the torch to prevent an accidental back flow from the torch.

b. Conditions

Specimen Size	.250"x2"x2"
Torch to Specimen Distance,	1.0"
Angle of Impingement,	90°
Total Gas Flow,	300 scfh
Oxygen/Acetylene Ratio,	1.17
Flame Temperature,	5450°F
Flame Condition,	Slightly oxidizing
Duration of Test,	Burnthrough or 400°F back temperature

c. Calculations

Insulation Index, sec/in, $I_1 = E\ (400F) + t_o$

Erosion Index, mils/sec $I_e = t_o + E_{bt}$

d. Where

$E\ (400°F)$ = Exposure time for back surface temperature to reach 400°F

E_{bt} = Exposure time for specimen to burnthrough, sec.

t_o = Original thickness of specimen, inch.

5. Aerojet-General Corporation

a. Apparatus, (see Figure 3)

Torch Tip	Airco No. 7
Oscillating torch holder assembly	
Specimen holder assembly	
Springloaded thermocouple assembly	
Electric motor, 1/4 horsepower	
Oscillating drive mechanism	
Timer	
Temperature recorder and Potentiometer	
Amplifier	
Start-Stop and Micro-Switches	
Thermos bottle	
Pressure gauges and regulators	
Portable console unit	

b. Test Procedures

Sample thickness and weight are measured before each test.

The test specimen is inserted in the specimen holder assembly and thermocouple connections made.

The torch tip is adjusted perpendicular to the specimen surface and then retracted to standby condition.

The torch is ignited and adjusted to the desired conditions then manually actuated to the test position after the master switch is turned on.

The oscillating mechanism and timer are turned on by a microswitch when the torch is actuated to the test position.

The test is continued for 30, 60 or 90 seconds or when the back surface temperature reaches 400°F.

c. Test Conditions

Specimen Size,	.250"x2"x2"
Torch Distance,	1.0"
Angle of Impingement,	30° to 150° (total arc angle of 120°)

Cycles per minute,	10 cpm (may be varied)
Oxygen/Acetylene Ratio,	1.1 to 1.0
Gas Flow Rate,	71 cu.ft./hr
Flame Temperature,	5270°F
Flame Condition,	Slightly reducing
Duration of Test	30,60,90 seconds or when back temperature reaches 400°F.

d. <u>Calculations</u>

Total weight loss, lbs. $W = W_o - W_f$

Total temperature rise, °F, $T = T_f - T_o$

Degraded layer thickness, in. $t = (t_v + t_d) - t_v$

Char thickness, inch $t_c = (t_v + t_d) - t_f$

Material loss rate, inches/seconds $MLR = (t_o - t_v) \div E$

e. <u>Where</u>

W_o = Original weight, lbs.

W_f = Final weight, lbs.

T_o = Original backside temperature, °F

T_f = Final backside temperature, °F

E = Exposure time total seconds

t_o = Original thickness, inch

t_v = Virgin layer thickness, inch

t_d = Degraded layer thickness, inch

t_f = Final thickness, inch

t_c = Char thickness, inch

APPENDIX B

B. Oxygen - Kerosene Torch Test

1. Bendix Aviation Corporation

a. Description

The oxygen-kerosene torch test is used for initial screening of high temperature insulating materials, prior to subscale and full scale motor testing. This test device consists of an oxygen-kerosene torch operated at supersonic gas velocities.

b. Test Conditions

Torch Nozzle Diameter	.500"
Torch Distance	2"
Angle of Impingement	60°
Flame Temperature	4500°F
Mach Velocity	1.8
Duration of Test	Specimen burnthrough

c. Calculations

Original thickness, inch	t_o
Final thickness, inch	t_f
Exposure time, seconds	E
Ablation rate, inches/second	AR = t_o ÷ E_{bt}

C. Plasma Test Devices

1. Atlantic Research Corporation

a. Plasma Jet

(1) Description

Atlantic Research is currently experimenting with a plasma jet to develop a screening test more closely simulating rocket conditions.

A spray nozzle and powder hopper are used to introduce solid particles into the flame to simulate the condensed phases present in some solid propellant rocket combustion products. A mixing nozzle is used to blend reactive gases into the plasma past the arc so that reactive plasma compositions may be obtained without electrode corrosion and contamination. An expansion flame exposure at reduced flow velocities, is used to simulate rocket high temperatures with low erosion.

(2) Apparatus

Plasma Torch, Model R 1-80 KW (Thermal Dynamics Corporation)

Control console for regulation of multiple gas flow and electric power input.

Two 40 KW rectifier-type D.C. power supply units.

(3) Conditions

The plasma torch is operated with nitrogem, argon, or helium gas at any mixture of these gases.

Power input with diatomic gases to the arc, 40 - 80.

Enthalpy level with diatomic or noble gases, BTU/lb, 12-16,000.

2. Aerojet-General Corporation

a. Plasma Jet

(1) Description, (see Figure 4)

The plasma jet is an arc-gas device capable of heating gases to extremely high temperatures. No combustion is involved. An electric arc is contained within a water cooled tube through which gas is blown. The gas issues from the plasma jet and resembles an open welding flame. Since no combustion is involved, the gas temperatures are not limited by internal heats of reaction. By continually adding electrical energy, gas temperatures in the range of 39,000°F with some gases can be achieved, while hydrocarbon oxygen flame temperatures are limited to approximately 5600°F.

The unit used by AGC is a Gas Sheath Stabilized Plasma Jet, manufactured by the Thermal Dynamics Corporation, as shown in Figure 4. The arc path is between the solid tungsten cathode and the hollow water cooled copper anode. This unit operates on both monatomic and diatomic gases. The arc remains within the nozzle and is prevented from prematurely striking the wall by a sheath of gas which is much thicker than the arc diameter. The arc is allowed to strike through this gas sheath only after passing considerable distance down the nozzle. Vortex flow is not generally used and arc positioning is accomplished through gas flow pattern and control of turbulence.

(2) Condition

Power Input, KW	80
Gas Temp., °F	39,000
Maximum Enthalpy, BTU/lb	12-16,000
Gas Flow, lbs/sec N_2	0.0042
Test Section @ Mach = 4 (5 mm pressure)	0.63"
Test Section @ Mach = 1 (5 mm pressure)	1.75"

b. Plasmatron, (see Figure 5)

(1) Description

The plasmatron has recently been adapted for ablation testing of materials in alumina-containing subsonic plasmas. It has been found that alumina-containing plasmas adequately simulate internal rocket motor environments. Therefore, they are able to provide a qualitative test for materials.

The plasma jet has been calibrated over a wide range of heat fluxes with the enthalpy range designed to be as high as possible and still maintain the alumina particles in the liquid phase.

In order to prevent the buildup of a protective alumina coating on the ablating bodies, the specimens are inserted into an area of the plasma before thermal equilibrium between the argon and alumina occurs. This allows the plasma to pass off any deposited alumina as a gas.

(2) Conditions

Stagnation enthalpy, 1320-4210 Btu/lb

Free-Stream temperature, 7350 - 9470°K

Stagnation pressure, 1.0 - 1.5 atm.

Heat flux to a 1000°F
wall 815-1685 Btu/ft^{2}sec

Aluminum content, 21.1%

Mass flow rate, 5.11 lb/ft^{2}sec

Usual working medium, Argon

c. Hyperthermal Environmental Simulator, HES, (see Figure 6)

(1) Description

The Hyperthermal Environmental Simulator, HES, is a device that will simulate the internal environment of a solid rocket motor for the purpose of determining the heat transfer and ablation characteristics of candidate insulation materials. The HES shown in Figure 6 will handle six gases: CO_2, CO, N_2, H_2, H_2O, HCl and Al_2O_3 particles simultaneously and proportional to the desired theoretical propellant gas composition. The gases are brought up to the desired enthalpy level by a gas stabilized arc plasma generator.

(2) Conditions

The HES operational limits are as follows and are based on the available power supply of 1.0 megawatt:

Stream Temperature,	5640-6040°F
Gas Velocity,	100-800 ft/sec
Gas Flow,	0.15 lb/sec
Stagnation Enthalpy @ 0.05 lb/sec.	8000 Btu/lb
Stagnation Enthalpy @ 0.10 lb/sec.	4000 Btu/lb
Stagnation Enthalpy @ 0.30 lb/sec.	1330 BTU/lb
Stagnation Pressure	300-500 lb/in^2
Test Specimen Size	.750 in. diameter
Angle of Impingement	90°

D. Propane - Air Gas Motor

1. Atlantic Research Corporation

a. Description, (see Figure 7)

The propane air gas motor, PAG, test facility has been used principally for studying effects of operational conditions upon insulation and nozzle performance. This facility could provide a screening technique which simulates rocket motor conditions and configurations. The test includes extensive temperature measuring instrumentation.

Insulation specimens in the form of a sleeve are inserted in the motor aft of the combustion chamber.

Nozzle materials are tested by using a throat insert fitted on the aft end of the motor.

b. Apparatus

Air compressors
Propane gas supply in pressure tanks
Oxygen-hydrogen gas supply for pilot flame
Piping
Mixing valve
Control valves
Thermometers
Pressure gauges
Manometers
Flowmeters
Dessicators
Water supply for water jacket cooling
Settling - Chamber
Faired orifice nozzle
Verticle flow test chamber 1 1/2 inch
Cone type flame stabilizer
High voltage ignition spark equipment for
 pilot light
Vent stock

Cylindrical water cooled chamber for
insulation test tubes 4" x 1-1/2" ID
Water cooled chamber for nozzle inserts 2-3/4"
long with 3/4" throat
Special minature high temperature thermocouples
for test specimens.
Timers and 12 channel visicorder recorders

c. Test Conditions

The test conditions for each specimen are selected within the ranges of the following parameters:

Temperature

Propane gas - air mixture flame temperature to 2500°K (4040°F).

Fuel Air Mixture

This can be manipulated through a limited stable range from rich to lean.

Mass Flow

Mass flow rate of gas is variable up to 1.0 lb/sec at pressure up to 100 psi. The approach velocity is variable up to 400 ft/sec, sonic or 3000 ft/sec if a nozzle is used.

Time

The duration of test is controllable and may extend to any desired period. Experience test range extends from 60 seconds to 10 minutes.

Turbulance

The degree of turbulance in the flame can be changed by insetting screens of varying mesh in the approach channel of the test chamber.

Abrasive Particles

Solid or molten particles can be injected into the flame; the relative concentration of the particles is controllable.

d. Flow Characteristics at Half Capacity are as follows:

Nozzle diameter	.750 inch
Test Chamber Diameter	1-1/2 inches
Mass Flow Rate (1/2 capacity)	0.50 lb/ft
Pressure (absolute)	71.3 psi
Approach Velocity, VU	60 ft/sec
Hot Gas Velocity, Vb	520 ft/sec
Density of gas in tube, cold	0.356 lb/ft^3
(G) in tube W/a	41 $lb/sec\text{-}ft^2$

e. Calculations

Conditions of gaseous flow.

Air - Fuel Ratio, Og

Gas Temperature, °F

Mass Flow Rate, lb/sec.

Pressure, psia

Temperature as a function of time at two or three depths in all specimens.

Conditions of cooling water flow.
Inlet temperature as a function of time.
Outlet temperature as a function of time.
Continuous flow rate.
Duration of test, seconds.

Observations of tested specimens:

Original weight, lbs, = W_o

Final weight, lbs = W_f

Weight loss, %

Original thickness, inch, = t_o

Final thickness, inch = t_f

Char thickness, inch = t_c

Virgin material thickness, inch = t_v

Nature of surfaces

f. Analysis of Results

The structural properties of the insulation specimen are determined from measurement of thickness, weight change, and from visual ovservation.

The rate of heat transfer within and out of the insulation is determined from the temperature records. Combined with the values of gas flow, this data furnished relationship for mass and heat exchange between the hot gases and the insulation specimen.

It is possible to observe the temperature and time that the various phase and material changes take place in the materials by studying the shape of the time-temperature curves. This permits an empirical correlation of the erosion and ablation heat transfer as functions of the flow parameters and properties of the materials.

Generalized oxidant fraction (Og) is the ratio of the mass of air to mass of fuel divided by the sum of the ratio of mass of air to mass of fuel plus the ratio of mass of air to mass of fuel at stoichiometric. For all air Og-0, for all fuel Og-1.0 and at stoichiometric Og - 0.5.

$$Og = \frac{(air/fuel)}{air/fuel + (air/fuel)\ stoichiometric}$$

E. Hydrogen-Oxygen Test Motors

1. Naval Ordnance Laboratory

a. Description

The hydrogen oxygen test motor facility is an intermediate test device used principally for studying effects of operational conditions upon throat insert materials prior to solid rocket motor firings.

b. Test Conditions

Firing conditions are controlled by varying the throat insert dimensions as follows:

Nozzle Configurations	A	B	C
Nozzle Throat Diameter, inches	.350	.350	.350
Nozzle Length, inches	1.278	1.578	2.143
Nozzle Exit Diameter, inches	.632	.759	1.000
Chamber Pressure, psia	200	397	588
Total Mass Flow Rate, lb/sec	.095	.197	.280
Exit Mach No.	2.2	2.5	3.0
Stoichiometric Mixture O_2/H_2= 8.0 (weight ratio)	3172°C 6200°R	3216°C 6280°R	3233°C 6310°R

c. Calculations

Throat diameter increase after firing, mils.

Time from design chamber pressure to 200 psig, seconds.

Erosion resistance, mils/sec.

2. Avco Manufacturing Company

a. Description

The hydrogen-oxygen motor was designed to evaluate materials to be used for fabrication of rocket nozzles. The facility is used to perform preliminary material evaluation.

The engine consists of three separate units:

An injector

Combustion chamber

Exhaust nozzle.

Each unit is water cooled. Depending on the test to be performed, any unit can be replaced readily by one that is solid-uncooled such as found on solid-propellant rocket systems. The fuel is gaseous hydrogen and the oxidizer is gaseous oxygen.

One special feature of the facility is that foreign powders, liquids, or gases can be introduced (at the injector plate) into the main stream of gas to simulate particle impingement, chemical and other effects.

Rocket nozzle material evaluation consists of exposing the inner diameter of blast tube or rocket nozzles to exhaust gases of the motor and comparing the performance of the various materials.

b. Test Conditions

Dimension and performance of hydrogen-oxygen rocket test motor.

c. Dimensions

Combustion Chamber diameter, inches	4.0
Throat diameter, inches	1.70
Exit diameter, inches	2.13

d. Performance

Exit Velocity, ft/sec	9000
Nozzle Exit Mach No.	1.8
Thrust, lbs	182
Specific Impulse, lb force/lb, mass, sec.	256
Mass Flow Rate, lb/sec	.685
Stagnation Temperature, °F	5000°
Mixture Ratio, $H_2:O_2$	4:1
Heat Flux, Btu/ft^2	400 to 450 (for wall temperature range of 100 to 1600°F)

e. General

Chamber pressure from 1 to 20 atmospheres.

Adiabatic flame temperature from 3800 to 5800°F

Throat diameter from 0.700 to 3.0 inches

Combustion-chamber diameter from 3.5 to 4.0 inches

Maximum operation time, 15 minutes.

f. Calculations

Original throat diameter, inches.
Final throat diameter, inches.
Time at full pressure, seconds.
Chamber pressure, operating and final, psia.
Surface temperature, °F.
Effective heat of ablation, BTU/lb.
Ablation rate, inches/sec.

3. Aerojet-General Corporation, Azusa

a. Description

The structural plastics ablative rocket, SPAR, test motor is a gaseous hydrogen-oxygen motor for evaluation of materials under rocket nozzle conditions. Sonic orifices located upstream in the propellant lines provide a constant propellant flow rate into the combustion chamber over a wide range of chamber pressures. The flame temperature is controlled by the fuel mixture ratio. Initial chamber pressure is controlled by propellant flow rate. Ignition is accomplished by a spark wire inserted on the test nozzle.

Instrumentation provides a continuous record of nozzle throat erosion rate, as well as the motor performance parameters that influence nozzle environmental conditions. Chemical attack on test materials may be studied by the introduction of contaminants.

The SPAR motor, however, does not reproduce the actual environment of a specific motor.

b. Conditions

Chamber Pressure,	Up to 800 psi, 500 psia with .500" dia. throat
Flame Temperature,	6100°F
Duration,	Up to 200 seconds
Test Specimens,	Nozzle throat insert, usually 1/2" dia. throat
Thrust Approximate,	130 lbs. using a .500" dia. throat
Mach No.	1.0 at the throat

APPENDIX B

F. Oxygen-Acetylene Motor

1. Aerojet-General Corporation, Azusa

a. Description, (see Figure 8)

The RIME, Rocket Insulation Material Evaluation facility is basically a gaseous fuel rocket motor designed primarily for the thermo-physical evaluation of materials in a high temperature, high heat flux, moderate velocity environment. Acetylene and gaseous oxygen are combusted in an enclosed flame head. Provisions are made for aspiration of metallic or other particles into the flame to simulate the flame composition resulting from the combustion of solid propellants.

b. Apparatus

Control Devices

- Oxygen and acetylene pressure regulators
- Mixing chambers
- Chamber pressure regulator
- Chemical particle asperator

Measuring Devices

- Oxygen-acetylene flow meters
- Chamber water flow meter
- Thermocouple pickup and recorder
- Chamber water calorimeter

Safety Devices

- Flame arresters
- Nitrogen purging gas

c. Calibration

Temperature: Flame temperature is calculated from stoichiometric combustion.

Heat Flux: Heat flux is measured by a water cooled calorimeter having the same relationship to the flame as the test specimens.

Chamber Pressure: Chamber pressure is measured manometrically.

Flame Velocity: Determined from differential pressure (pitot tube).

d. Special Features of the RIME

Heat flux, flame temperature, flame velocity and chamber pressure may be accurately measured and reproduced.

Flame composition resulting from combustion of solid propellants may be simulated.

Specimens are tested in an enclosed chamber.

Firing duration is controllable to within 0.1 second.

Combustion gas flow is measured with an instrument variation of ± 0.25%.

Specimen back surface temperature determined by spring loaded thermocouple and recorded for direct read out.

Nitrogen purge before and after test firing.

e. Test Conditions

Pressure	To 30 psia
Temperature	3800°F to 6300°F
Heat Flux	To 650 BTU/ft^2, sec.
Flame Velocity	Mach 0.1 to 0.7

Flame Characteristics - Reducing, Neutral or Oxidizing (as required).

f. Calculations

Test specimens surface area, ft^2, A

Heat input, (as measured with a calorimeter) Q_o - BTU ; ft^2/sec.

Heat of Ablation: $\frac{BTU}{lbs}$; $Q^* = \frac{Q\ A\ E}{W}$

APPENDIX B

Exposure time, seconds	E
Total weight loss, lb	$W = W_o - W_f$
Char thickness, inch	$t_c = t_f - (t_v + t_d)$
Material loss rate, inch/sec.	$MLR = (t_o - t_v) + E$

Physical appearance before and after testing.

G. Suspensoid Propellant Motor (Slurry Test Motor)

1. Aerojet-General Corporation, Azusa

a. Description

The slurry test motor was developed to more closely simulate the chemistry of aluminized solid propellant fuels. The propellant is in the form of a thixotropic paste containing suspended aluminum particles, and the fuel composition closely resembles the solid propellant from which it is derived. The combustion products of the slurry propellants duplicate those of the parent solid propellant.

The motor is fired vertically, with the pool burning propellant encased in an insulated shell. Instrumentation is used providing a continuous record of chamber pressure and thrust.

The use of slurry propellant provides the possibility for voluntary termination of a test firing, so that failure patterns may be studied from the post-fired specimens.

b. Conditions

The suspensoid motor is currently operable for firing durations of 15 seconds maximum, at 1000 psia using a nozzle insert with a .500" diameter throat. Modifications may be made to the existing facility in order to obtain longer firing durations and voluntary termination of the test cycle.

Chamber pressure	1000 psia
Flame-Temperature	5400°F
Mach No.,	1.0 at the throat

H. Subscale Solid Propellant Test Motors

1. Atlantic Research Corporation

a. Description, (see Figure 9)

(1) Test Motors: For maximum flexibility, end-burning test motors are used. Burning time is varied by varying grain length, and pressure is varied by changing the burning rate or the throat area. The burning rate is changed by embedding fine axially-oriented wires in the propellant.

Thermocouples are custom made in the ARC laboratories. Special refactory metal thermocouples are used above the chromel-alumel temperature range. Recording equipment includes Minneapolis-Honeywell Visicorders, Midwestern Instrument Company records and Alinco K-4 Ballistic Computer.

(2) Propellants: One of the most important variables in testing is the propellant since the effects of flame temperature and chemical reactivity of the gas are critical. A single propellant could be used for a specific test program where the objective is to simulate a specific rocket motor condition, but because of these effects, it is not possible to conduct any general testing with a single propellant.

A group of three propellants have been selected for general material studies. These propellants range from Arcite 368 containing no aluminul, to Arcite 373 containing 21 percent aluminum. An intermediate propellant, Arcite 394, contains 7.75 percent aluminum. Materials which react with CO_2, H_2O, or HCL will undergo erosion in Arcite 368 exhaust because of its high content of these three constituents. Materials which react with molten aluminum oxide or which melt between 4600°F and 5600°F are likely to perform poorly in the gas of Arcite 373.

b. Component Testing

Motor tube insulation, nozzle insulation, nozzle throat insert; expansion cones and jetevator impingement bars are tested in the test motors. All of these components can be tested simultaneously during a motor firing if desired.

(1) Motor Tube Insulation

The testing of insulation materials as chamber liners is conducted in a hybrid test motor (so-called because of its unique construction features). A schematic drawing of this motor is shown in Figure 9. Previous testing has generally been with the 64-inch long, 6-inch diameter propellant section which operates for 60 seconds at 1000 psi. The motor-tube insulation section is 24 inches long, with a nominal inside diameter of four inches. The test specimen tubes have matched tapered joints and are cemented to form one internally-smooth, continuous tube. Dimensions of the tube can be changed. Normally, six cylindrical specimens are tested during each firing and temperatures are measured at diametrical points on a cross-section taken through the mid-point of each tube. The thermocouples and a magnified sketch of thermocouple assembly are shown in Figure 9.

(2) Nozzle Insulation

Insulation materials are tested on the convergent face of the nozzle, and in the section of the nozzle. A nozzle assembly for the 6-inch motor is shown in Figure 10. The nozzle insert is thermally insulated from the nozzle assembly to duplicate light-weight flight conditions.

Six panel specimens are tested simultaneously on the convergent face with each specimen being independantly embedded and instrumented for temperature measurement. After testing, these specimens are removed from the bedding cement and measurements are taken of the surface erosion, depth of degradation, and amount of unaltered material. The firing results are coordinated with data from the continuous temperature measurements. The nozzle test assembly can be used in any length motor to obtain a comprehensive evaluation of insulation materials for many exposure conditions.

(3) Nozzle Insert Insulation

Testing insulation materials for the throat insert follows a simple technique. The insulation is incorporated in the nozzle assembly around the insert as shown in Figure 10. Results are evaluated by temperature readings on the cold side of the insulation and by the insulator's ability to retain effectively the insert and form a gas seal around it.

(4) Expansion Cones (Exit Cones)

The divergent test section is a simple conical piece separately mounted in the expansion section of the nozzle. Although Figure 10 does not show thermocouple instrumentation of the expansion-cone test piece, several thermocouples are inserted into test pieces. Results of testing are measured in a manner similar to that for convergent test parts.

(5) Jetevator Impingement Testing

Jetevator tests are made at ARC. The specimens are bars, 1/4" x 3/8" x 1-1/4", bounted in such a way that they can be introduced into and removed from the motor exhaust at will; normally they are exposed for two seconds and then out for two seconds. The number of cycles employed during a run is dependant on the firing duration of the motor. The 3/8" wide face is exposed approximately 1/16" into the flame at 73.5° to the cone edge. The specimen is backed up with a micro-quartz insulator and molybdenum backup bar. Changes of profile indicates the effects of the exposure to the specimen.

c. Calculations

(1) Insulation

Char depth, in.
Erosion depth, in.
Exposure time, sec.
Temperature, cool side, °F
Chamber pressure, psi
Weight loss, %
Physical appearance after test

(2) Throat Inserts

Chamber pressure, psi
Firing duration, sec.
Throat diameter, before and after firing, in.

2. Allegheny Ballsitics Laboratory

a. Description

Several types of subscale test motors are used for the evaluation of nozzle and insulation materials. Test motors are "end burning" and use a solid propellant fuel. Conditions are controlled by the selection of propellant, nozzle design and size of the motor used. Characteristics of the propellant used most frequently are as follows:

Propellant Identification	Theoretical Flame Temperature	Percent Aluminum
CDT - 80	6000° - 6373°F	20.0

CDT - 80 is a modified double base propellant containing aluminum and ammonium perchlorate.

Test methods used for the evaluation of chamber insulation, nozzle insulation, and nozzle throat inserts are described as follows:

b. Chamber Insulation

(1) Slab Test, (see Figure 11)

This test consists of exposing a .375" x 2" x 4.375" insulation specimen to hot gases on the approach nozzle section of a subscale test motor as illustrated on Figure 11. CDT-80 propellant is used to yield the following conditions:

Gas Velocity - 100 - 130 ft/sec.
Temperature 3000°K (6375°F)
Burning Time - up to 30 seconds
Pressure - 250 - 1000 psi

At the end of the firing the motor is flushed with CO_2 to prevent spontaneous ignition of the hot insulation residue.

(2) Peripheral Slab Test

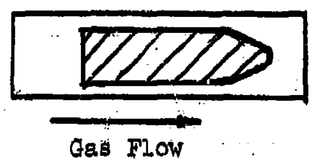
The peripheral slab test consists of exposing a single face of a 2" x 4" x 3/8" slab of insulation to rocket combustion gases. Eight specimens may be tested simultaneously as they are fastened to the inside of the insulation sleeve placed in the aft section of a single end burning motor. This test apparatus permits convenient evaluation of material over the following ranges of variables:

Exposure Time	10 to 60 seconds
Pressure	200 to 2000 psi
Gas Velocity	30 to 80 ft/sec

At the end of the firing the motor is flushed with CO_2 to prevent spontaneous ignition of the hot insulation residue.

This test was divised to avoid the difficulty encountered in the regular slab test with certain materials, particularly at high pressures (700 psi). This difficulty is manifested as a tendency toward steam lining of the specimen as shown below:

Slab Cross Section



The presence of this phenomenon makes the evaluation of char or erosion depth difficult or impossible.

(3) Blast Tube

In order to study the profound effect of gas velocity on insulating materials, a blast tube containing the insulation specimen is fitted to the aft end of the five inch test motor illustrated in Figure 11.

The specimen consists of a tube, the diameter of which may vary between 3/4" and 1-1/2" depending upon the velocity desired. The blast tube in conjunction with the peripheral slab test permits the evaluation of insulation performance over throat-to-port area ratios ranging from .009 to .9 or gas velocities of 500 to 1200 ft/sec with VH1 propellant. The major disadvantage of this test method; namely, the inability to maintain constant velocity across an erodable material in the blast tube. At 250 psi the char rate for asbestos phenolic almost doubles going from 50 ft/sec to 1200 ft/sec.

c. Nozzle Insulation Test, (see Figure 12)

Nozzle insulation materials are tested on the entrance and exit sections of the nozzle assembly. This testing involves the use of a very high impulse propellant, CDT-80, in a 9" test motor illustrated on Figure 12.

d. Throat Inserts, (see Figure 13)

The evaluation of nozzle throat materials are called out by testing the throat inserts in the three, five and nine inch diameter sub-scale test motors using a double base aluminized propellant containing ammonium perchlorate. Figure 13 illustrates the five inch diameter test motor used most frequently.

e. Calculations

(1) Insulating Materials

Char depth, inch $CD = (t_o - t_v) \div 2$

Erosion depth, inch $ED = (t_o - t_f) \div 2$

Exposure time, sec.

Temperature cool side, °F

Char rate, mils/sec $CR = (t_o - t_v) \div E$

Erosion rate, mils/sec $ER = (t_o - t_f) \div E$

Chamber pressure, psi

Total weight loss, lbs $W = W_o - W_f$

Physical appearance after test

Ideally, materials tested by the above methods are evaluated in terms of char depth or the depth of the altered material. This concept is based on the premise that a material is behaving as an effective heat barrier as long as unaltered organic material remains. Some materials degrade in such a peculiar fashion that it becomes inconvenient or impossible to rate them according to rate of char.

(2) Nozzle Throat Inserts

Chamber pressure, psi

Firing duration, sec.

Throat insert diameter before firing, in.

Throat insert diameter after firing, in.

Throat insert diameter after removal of Al_2O_3 deposits, in.

Physical appearance after test.

3. <u>Aerojet-General Corporation</u>

a. MERM

(1) <u>Description, (see Figure 14)</u>

The Material Evaluation Rocket Motor, MERM, is a subscale test motor used for the evaluation of candidate nozzle and insulating materials. The MERM has an end burning, 8-inch diameter, case bonded grain. Test conditions are controlled by changing the nozzle insert design and the choice of propellant type. Changes are made as required to simulate the latest POLARIS operating conditions. Figure 14 illustrates the MERM assembly.

Insulation materials are tested on the convergent section of the nozzle assembly in the form of a throat insert entrance cap as shown in Figure 15.

(2) <u>Conditions</u>

Duration, 60 seconds

Chamber Pressure, 1000 psia

*Flame Temperature, 5200-6500°F

Velocity, Mach. No. 1.0 at the throat

Throat Diameter .489"

*Varied dependant on project requirements and propellant developments.

b. <u>RITE</u>

(1) <u>Description, (see Figure 16)</u>

The RITE motor is a subscale rocket motor similar to the MERM with an extended motor casing which houses an insulation test specimen. Material candidates for RITE motor tests are formed into bell mouthed straight blast tubes of various diameters which produces the same range of gas velocities present in full scale motors. Plots of material loss rate versus velocity facilities selecting the proper thickness of material for various velocity regions in the full scale motors. The aft end of the extended motor casing employs a porous graphite throat insert fitted with a water tap. Chamber pressure is controlled by maintaining a constant water pressure, on the throat insert, which eliminates or reduces erosion of the throat. Figure 16 illustrates the RITE test motor.

APPENDIX B

(2) <u>Conditions</u>

*Flame Temperature,	6000°F
Chamber Pressure	Approximately 350 psia
Throat Diameter,	.583"
Gas Velocity,	Pending on inside diameter of test specimen Mach .03 to .30.

(3) <u>Calculations</u>

A = Test specimen surface area, ft^2

Q_o = Heat input, $\frac{BTU}{ft^2/sec.}$, as measured with a calorimeter.

Q* = Effective heat of ablation in $\frac{BTU}{LB.}$,

$$\frac{Q_o\ A\ E}{W}$$

MLR = Material loss rate, $\frac{t_o - t_r}{E} = \frac{inches}{sec.}$

*Varied dependant on project requirements and propellant developments.

II. Comparison of Test Devices and Test Facilities

A. Test Devices

1. Oxyacetylene Torch

a. The most general accepted laboratory screening test for the evaluation of insulation materials is the oxyacetylene torch test. Testing is rapid, economical, and does not require elaborate equipment. However, a wide range of operating conditions exist between each test orgainzation and as a result, test data differs between each facility for a given material. Also, materials showing superior performance in torch tests often fail in solid propellant test firings.

b. The need for standardization has been recognized by the various test laboratories and as a result a proposed standard has been drafted by a joint ASTM-Navy Committee for the standardisation of oxyacetylene torch testing. (A brief summary of the proposed standard is included below.) The author's analysis of the results obtained during this survey, indicates that correlation will be difficult between oxyacetylene torch and subscale testing using the proposed test conditions. However, by using a high gas flow in the order of supersonic velocities, a correlation can be established between torch and subscale motor testing.

c. The oxyacetylene torch apparatus used by the AGC POLARIS Project utilizes an oscillating mechanism secured to the torch to create a more turbulent condition at the specimen surface to test the resistance of the spalling characteristics of the material.

d. The following proposed standard has been drafted as of 1 December 1960, by the Joint ASTM-NAVY Committee for the standardization of oxyacetylene torch testing.

APPARATUS

Oxyacetylene Torch, Capable of supplying specified has flow rates.

Torch Tip, Single port - - - - - - - - - - - - 0.130 in. ID

Total Gas Flow Rate - - - - - - - - - - - - - 225 Scfh. *

Volume Ratio of Oxygen to Acetylene - - - - - 1.20

Thermocouple Wire Size - - - - - - - - - - - - # 28B and S gage or smaller

Temperature Record Pen Response Time - - - - 1 second full scale or faster

Temperature Record Chart Speed, Min., - - - - 8-10 in/min

Transiont Calorimeter for Heat Flux Measurements

Pressure Probe for Flame Pressure Measurements

SPECIMEN

Size, 0.250 inch thick, remaining dimensions and configuration not specified.

PROCEDURE

Angle of Impingement - - - - - - - - - - - - - 90°

Specimen to Torch Tip Distance - - - - - - - - .750 in.

Maximum allowable to bring flame onto specimen-1/2 second

Termination of Test, after a backface temperature of 800°C (1472°F) has been reached (when possible). An optional procedure permits complete burnthrough of panel for measurement of erosion rate.

MEASUREMENTS

Thickness, weight and density of specimen prior to test.

CALCULATIONS

Insulation indices at 100, 200, 400, and 800°C (212, 392, 752 and 1472°F) by dividing the time to reach these temperatures by the original thickness of the specimen.

Erosion Rate, original thickness of the specimen divided by the time to burnthrough.

Insulation to Weight Ratio, Insulation Index divided by the original density of the specimen.

Arithmetic average of items 1-3 inclusive for five replicates.

Root means square deviation of items 1-3 inclusive for five replicates.

*Standard cubic feet per hour, 70°F, 14.7 lbs/sq. in.

2. Plasma Test Devices

a. The plasmajet, a more elaborate and versatile test device is capable of producing higher pressures, velocities, temperatures, and heat fluxes than those produced by any other test device discussed in this report. A wide range of operating conditions exist between the various units which is primarily dependant on the power output. Some units are capable of simulating the products of combustion found in solid propellant motor conditions by injection of mixed gases and solid particles in the plasmarc. The plasmajet is considered a good device for research purposes, but the cost of equipment and operating expenses, its use for insulation screening and intermediate testing should be carefully analyzed. Listed below is a comparison of the various plasma units and their applications used by the various test organizations.

(1) Plasmatron

A unit used by AGC, Azusa, for obtaining thermal data on prospective materials. Low pressure unit, 60 KW available power, can only simulate a narrow range of thermal conditions.

(2) Plasmajet

Both AGC-ARC units are similar and have a higher power output, 80 KW, than the Plasmatron. Capable of simulating rocket motor combustion products by injection of mixed gases and solid particles in the plasmarc.

(3) HEG

To operate at the same pressures, and heat fluxes as the POLARIS rocket motor. Gaseous products of combustion in solid rocket motors can be simulated by injection of gases and solid particles in the plasmarc. (1000 KW high pressure plasma generator)

Unit still in the construction stage. Expected to be operating in the near future.

3. Gaseous Test Motors*

a. Gaseous test motors are elaborate torch test devices, enclosed in a combustion chamber, where the test specimen is completely submerged in the gaseous products of combustion and subjected to a greater area of diffused heat transfer. Test motors are usually instrumented to measure the control operating conditions and to obtain specimen thermal data. Certain units are capable of injecting solid particles into the gas stream to test the characteristics of erosion on the specimen. However, insufficient heat flux is obtained which affects thermal reactions and their combustion products are different than those produced by solid rocket motors.

b. The cost of the equipment and its construction hardly warrants the use of the apparatus for screening and intermediate testing of insulation materials since screening tests can be accomplished with the inexpensive torch test. Insufficient heat flux and different combustion products than those produced by solid propellant test motors limit its use for intermediate or screening tests.

4. Subscale Solid Propellant Test Motors

a. The subscale solid propellant motor has been proven to be a versatile test device by offering a wide selection of propellants to give a range of time, temperature and pressures.

b. Both nozzle insert and external insulation materials may be tested simultaneously while some units, such as the RITE, utilizes a blast tube for the testing of internal insulation at high gas velocities.

c. Test results are closely related to full scale firings when firing conditions are duplicated.

d. The subscale solid rocket test motor has the disadvantages over laboratory test devices by relying on outside laboratory control for scheduling, processing, assembly and firing of the test motors.

e. The subscale test motor is considered the better test device for testing of materials prior to full scale firings. However, considerable improvement could be obtained by the standardization of test specimens, conditions, motors and propellants.

* Gaseous test motors defined in this report are test devices using a gaseous medium for producing combustion in an enclosed chamber, such as, the hydrogen-oxygen motor, acetylene-oxygen motor, and the propane-air-gas motor.

f. The following outline is a comparison of a subscale test motor used by the various test organizations:

(1) Atlantic Research Corporation

Well organized test program with a wide selection of propellants and motor sizes for obtaining test conditions desired. Reporting of test data is also well organized. However, no program has been established for the testing of insulation materials at high velocities. Test reports are not always consistent in reporting the source of test material.

(2) Allegheny Ballistics Laboratory

Excellent for their studies on the effects of operating conditions on insulation materials. First facility to incorporate a blast tube on their test motors for determining the effects of velocity on insulation performance.

Nominal test conditions often vary and test data is often inconsistent with no continuity from one quarterly report to the following.

(3) Aerojet-General Corporation

RITE - Capable of producing the same range of gas velocities as those occurring at various locations and times in full scale motors. Plots of material loss rate vs. velocity or mass flow rates facilitate the selection of material of adequate thickness for various velocity regions in the full scale motors.

Constant chamber pressure can be obtained by controlling the erosion of the throat insert by use of water pressure on the porous graphite insert. Established methods of reporting test data which is kept up to date in a firing log book.

MERM - Primarily used for evaluation of throat insert materials. Close correlation to full scale motors by selecting material combinations and thickness based on heat transfer and thermal stress studies.

Results on insulation testing are limited to relative comparisons between materials.

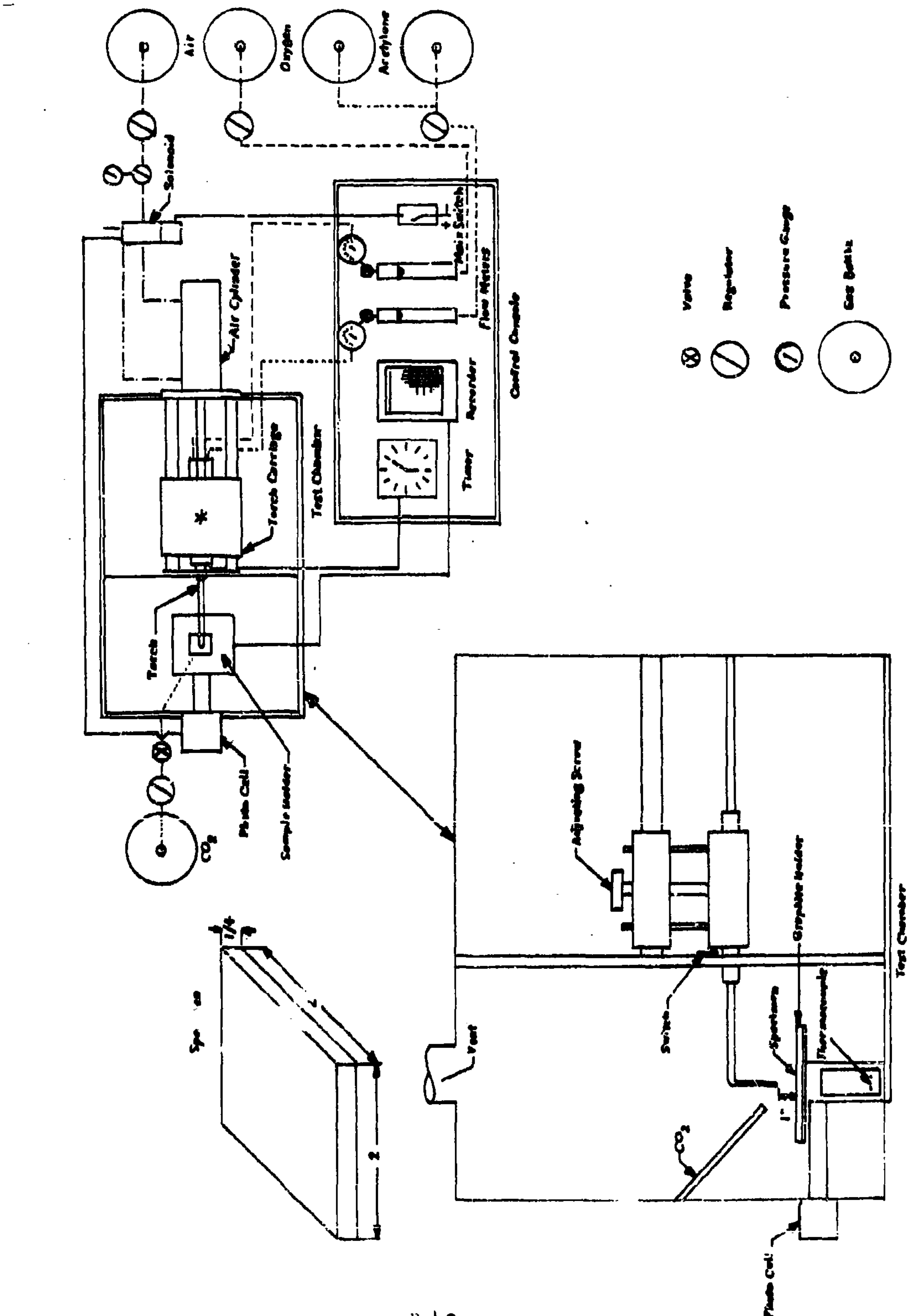


FIGURE 1
OXYACETYLENE TORCH TEST FACILITY
ATLANTIC RESEARCH CORP.

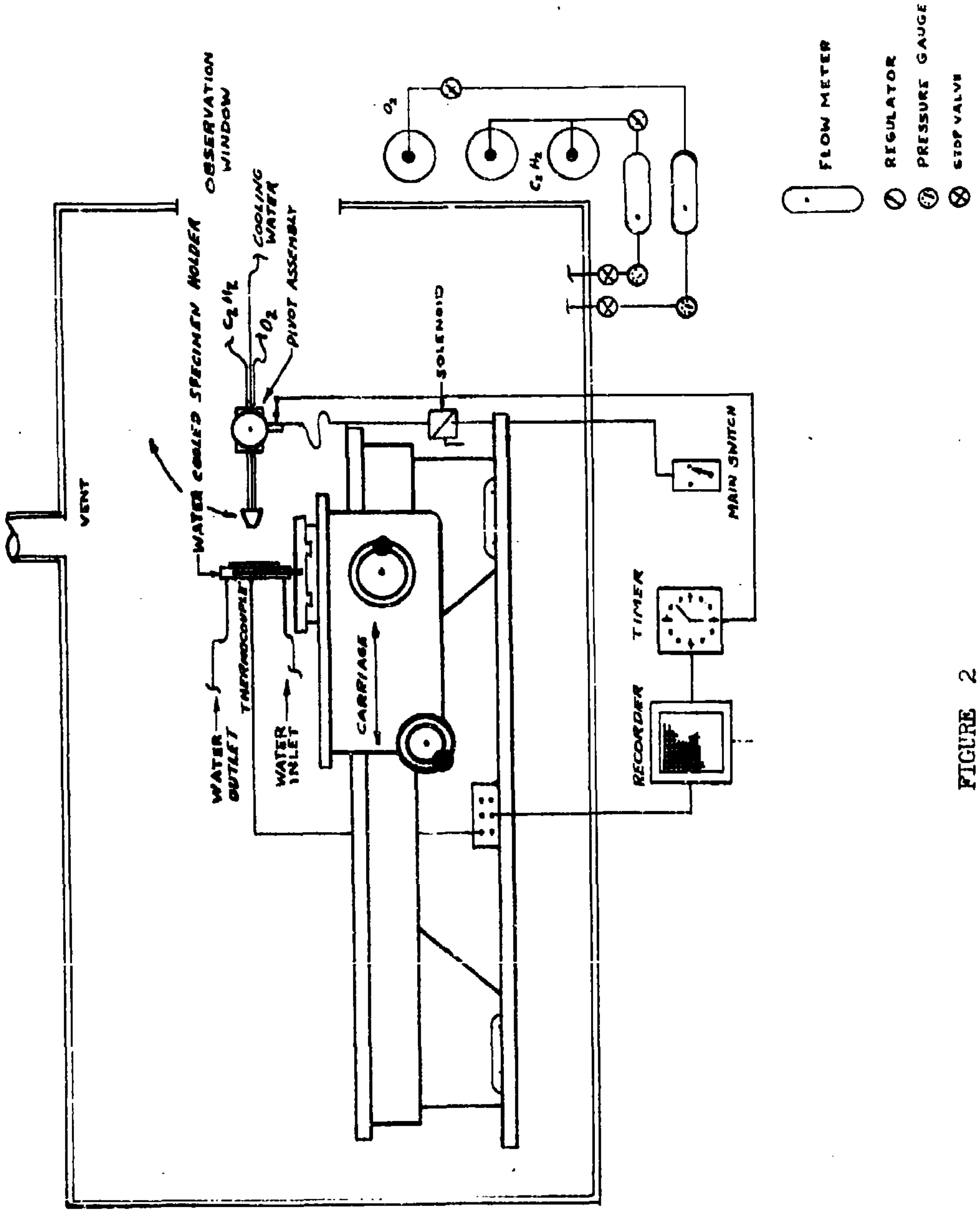


FIGURE 2
OXYACETYLENE TORCH TEST FACILITY
NAVAL ORDNANCE LABORATORY

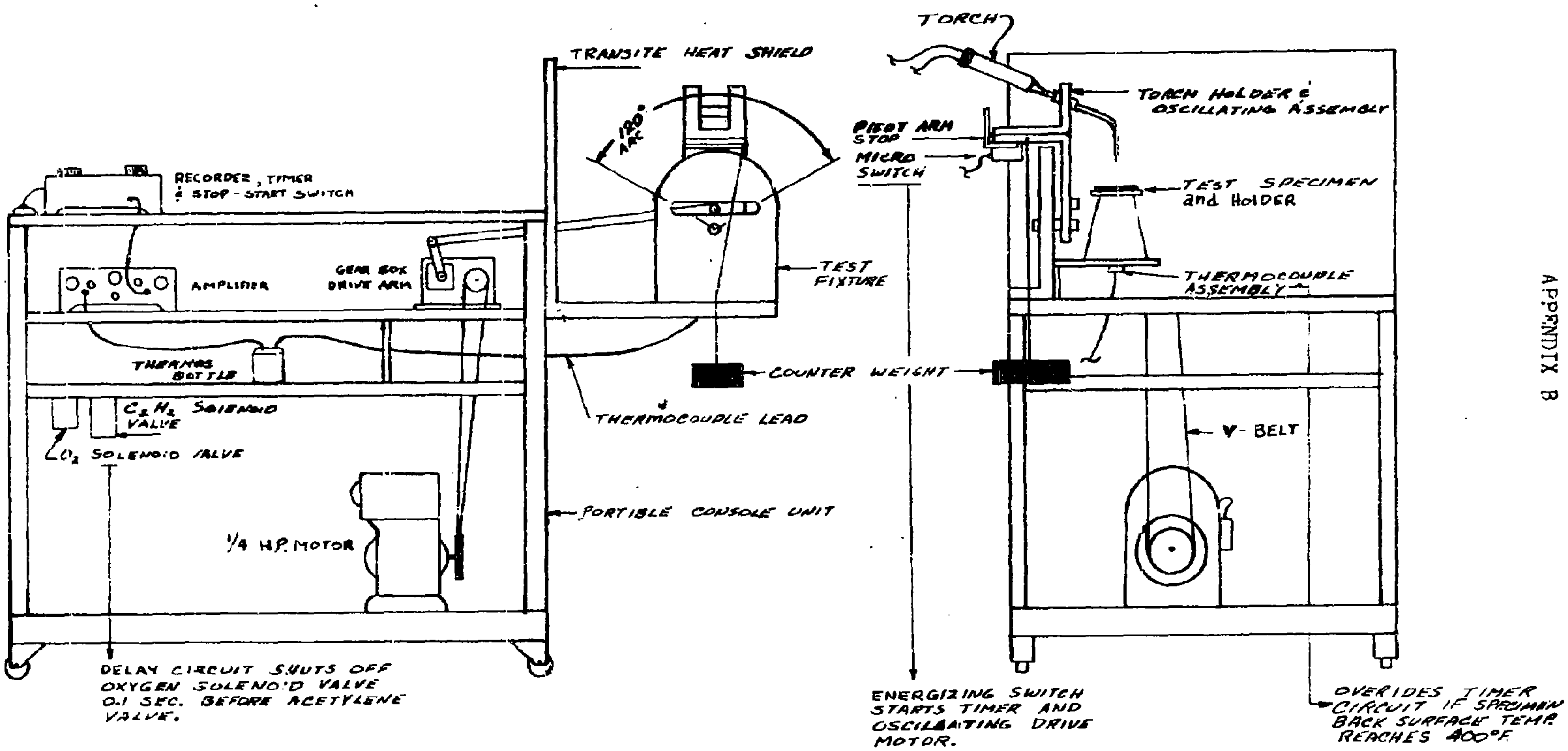


FIGURE 3
OSCILLATING OXY-ACETYLENE TORCH TEST FACILITY
AEROJET GENERAL CORPORATION

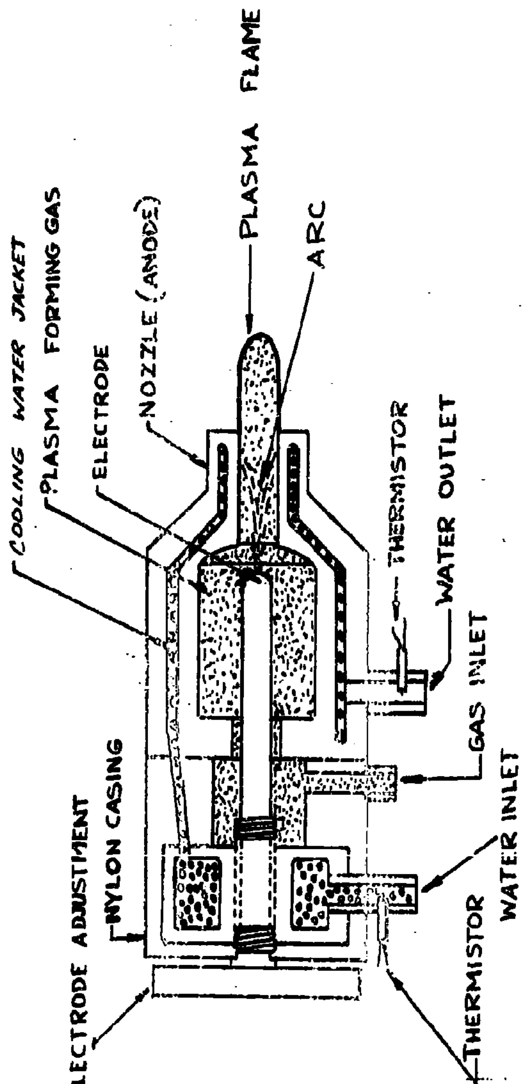


FIGURE - 4

GAS SHEATH STABILIZED PLASMA TORCH DESIGN

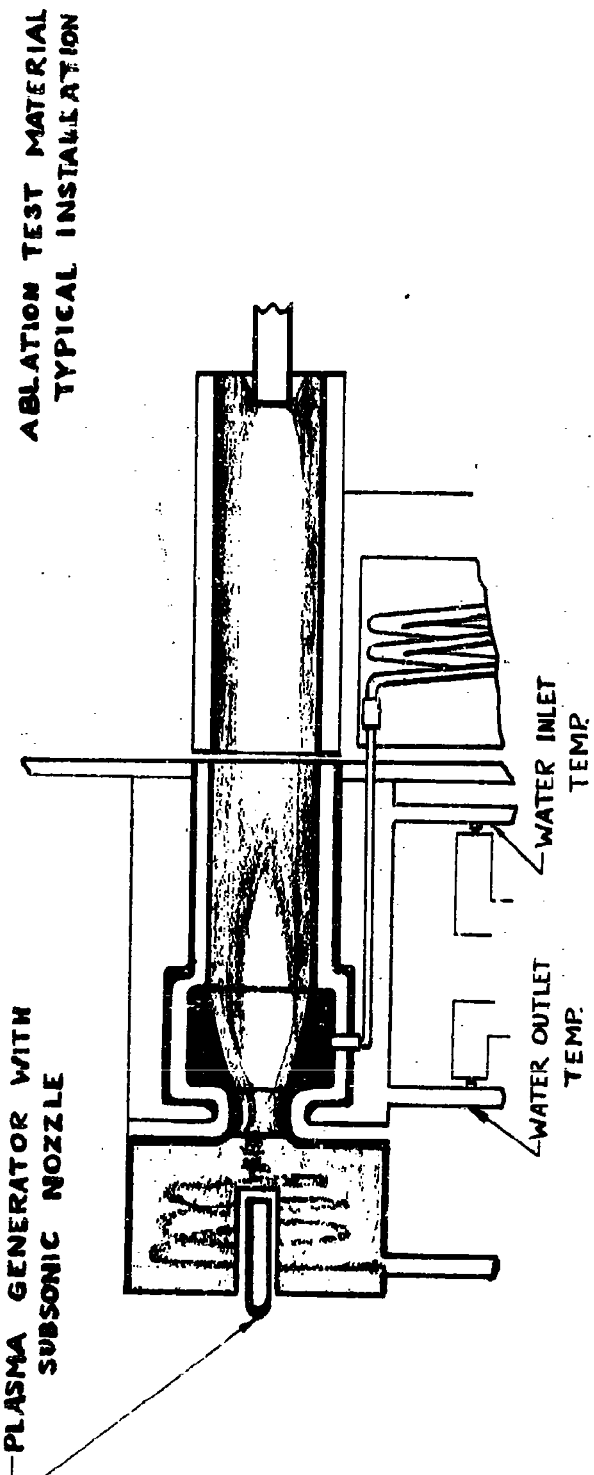


FIGURE -5

PLASMA ARC TEST DEVICE

-PLASMATRON-

AEROJET-GENERAL CORPORATION
(AZUSA)

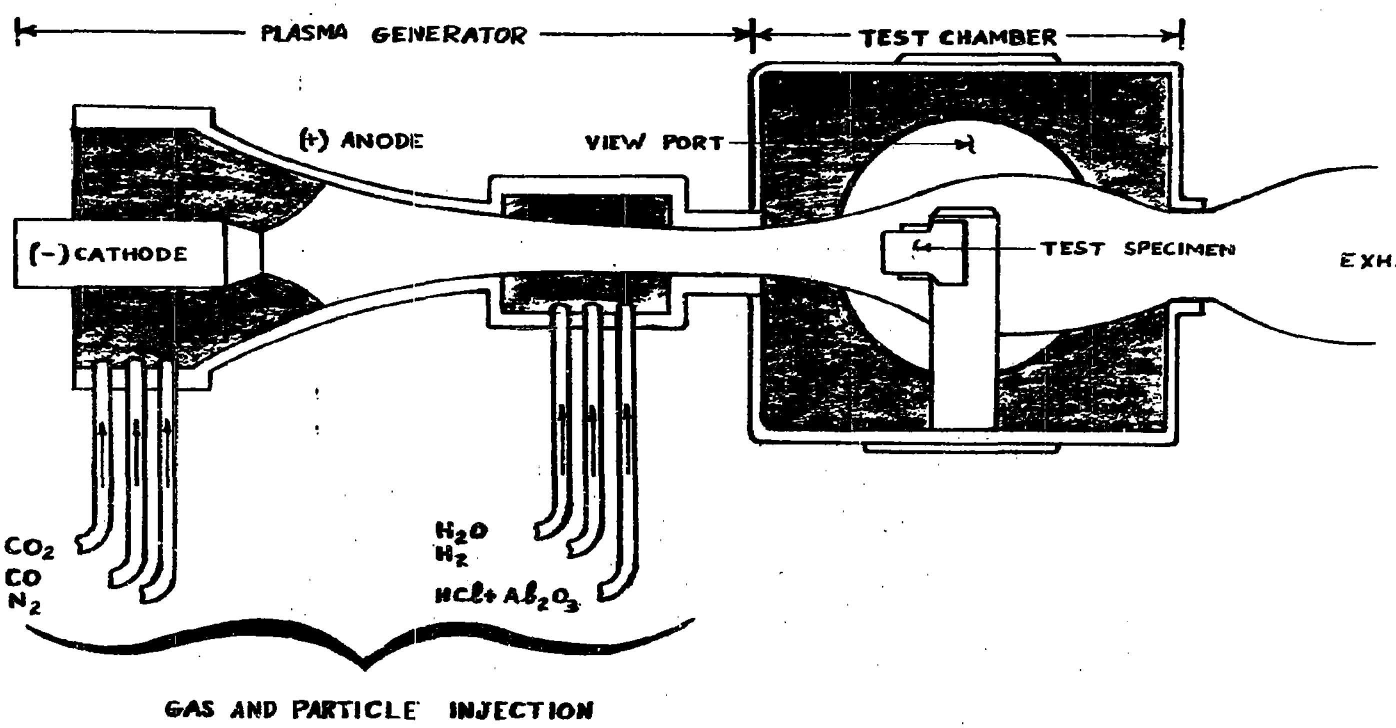


FIGURE -6

HYPERTHERMAL ENVIRONMENTAL SIMULATOR

-HES-

AEROJET-GENERAL CORPORATION
(AZUSA)

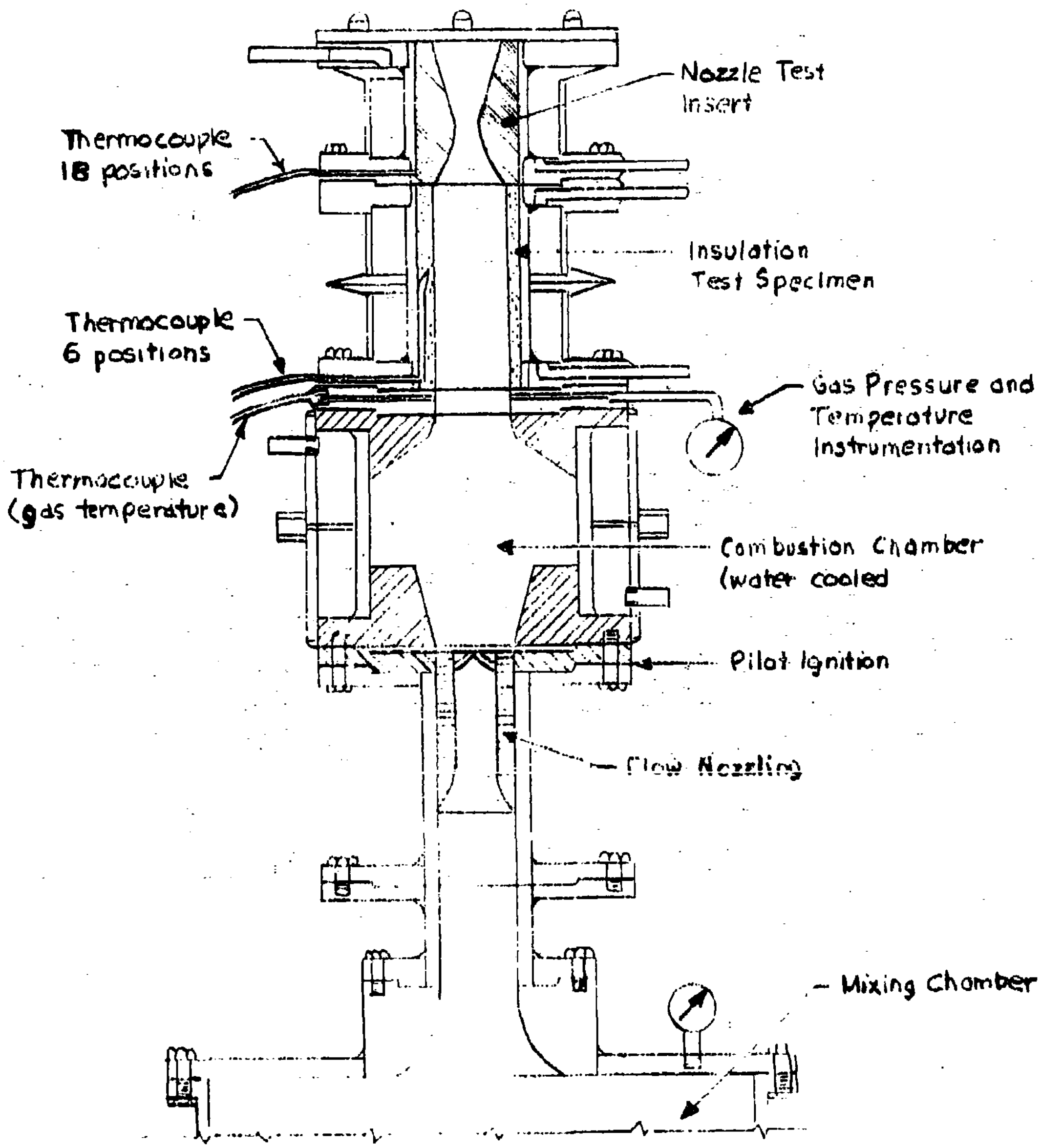


FIGURE- 7
PROPANE-AIR GAS TEST MOTOR, PAG
ATLANTIC RESEARCH CORP.

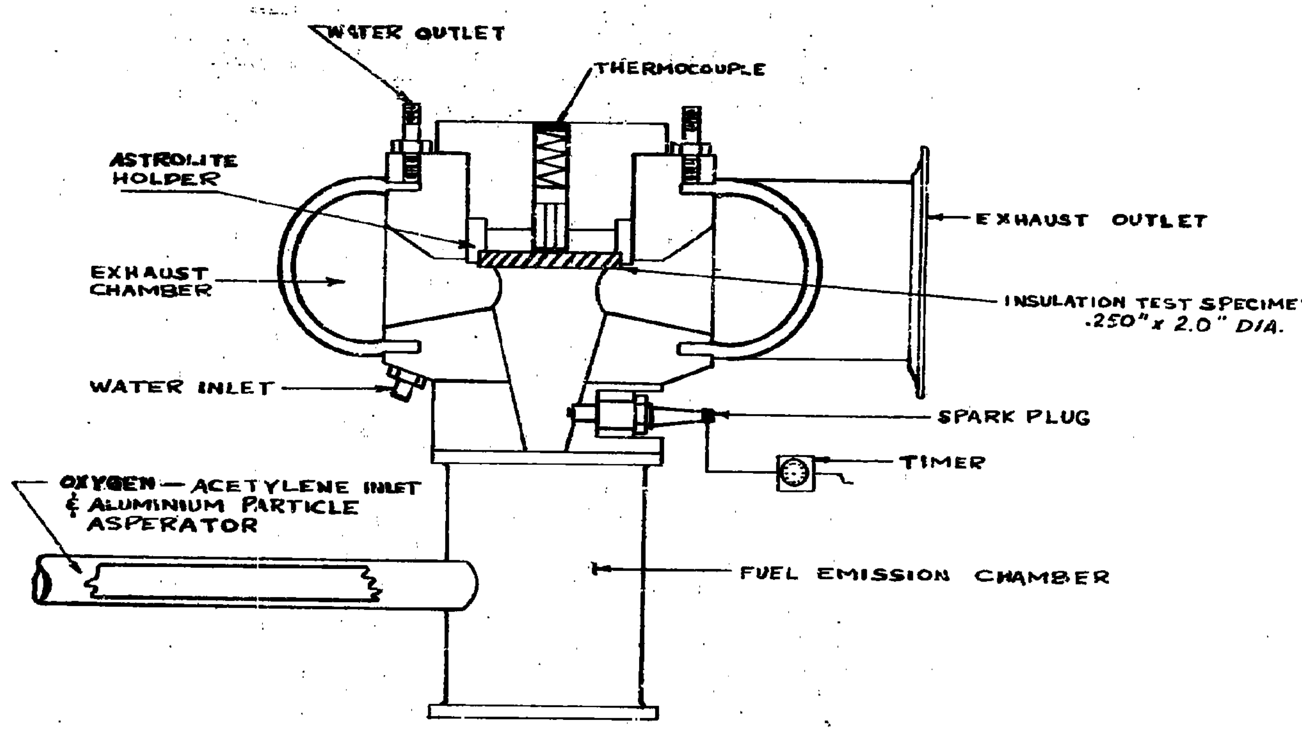


FIGURE 8

ROCKET INSULATION MATERIAL EVALUATION

-RIME-

AEROJET GENERAL CORPORATION
(AZUSA)

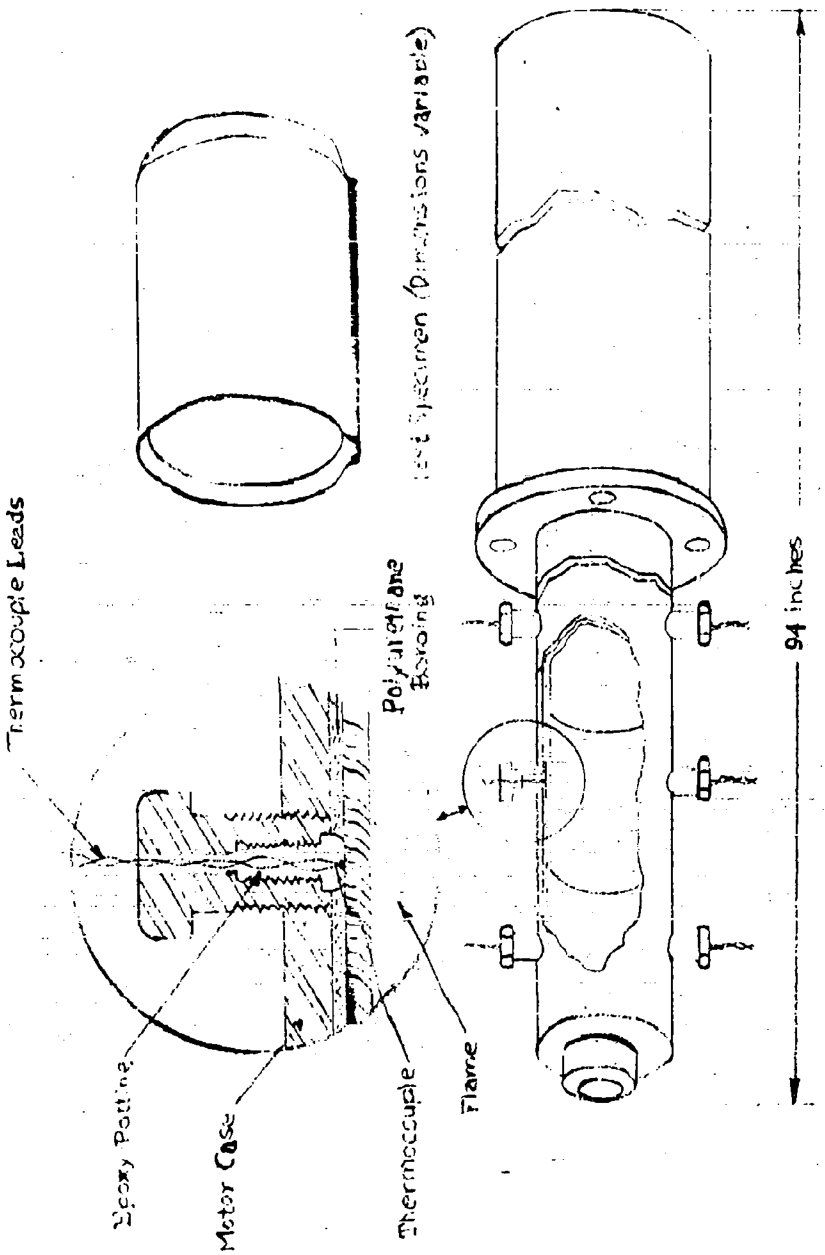


FIGURE - 9
SUBSCALE SOLID PROPELLANT HYBRID TEST MOTOR
FOR TESTING INSULATION SPECIMENS
ATLANTIC RESEARCH CORP.

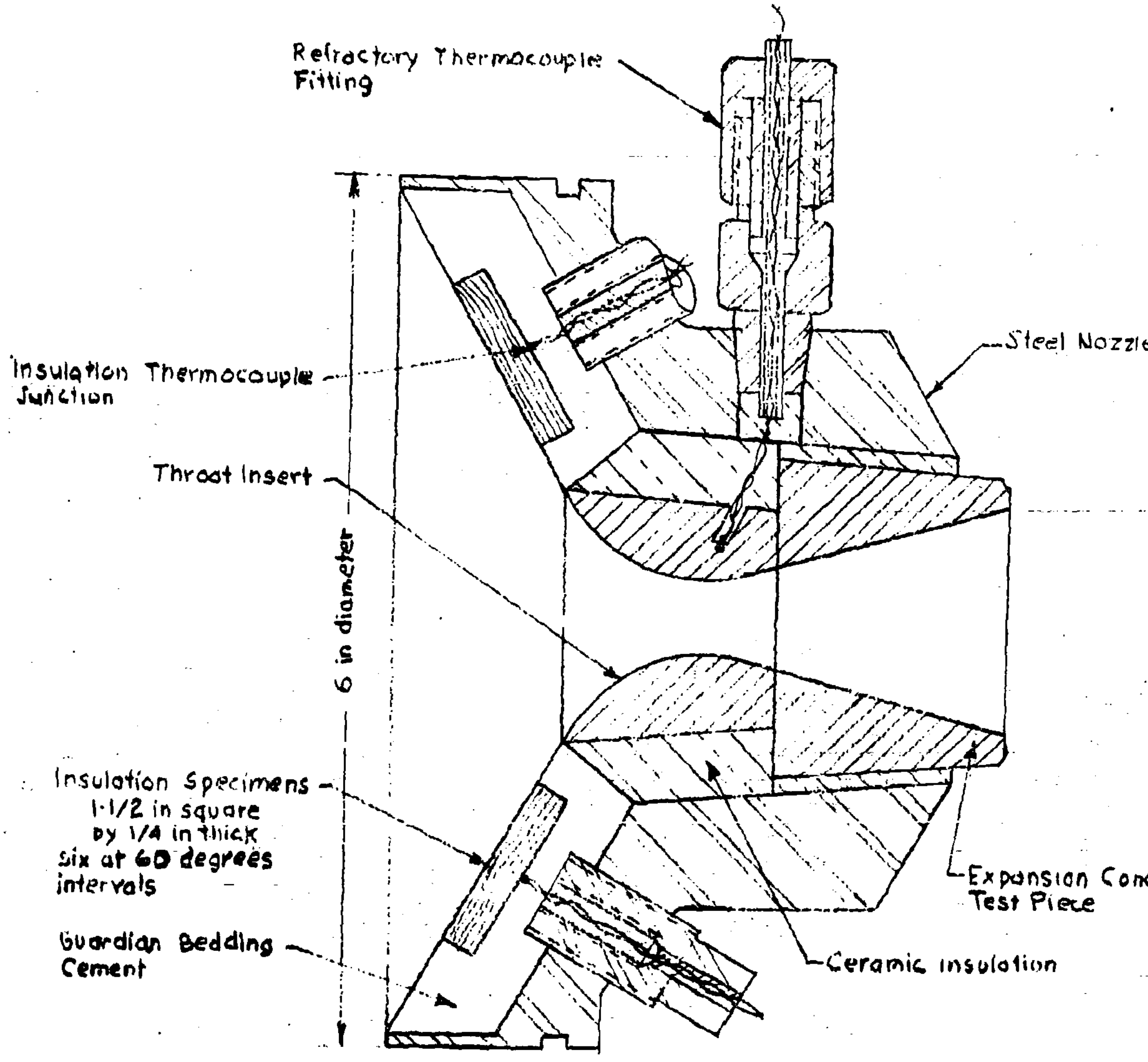


FIGURE - 10
SUBSCALE TEST MOTOR NOZZLE ASSEMBLY
SHOWING NOZZLE APPROACH INSULATION, NOZZLE INSERT AND EXPANSION CONE.

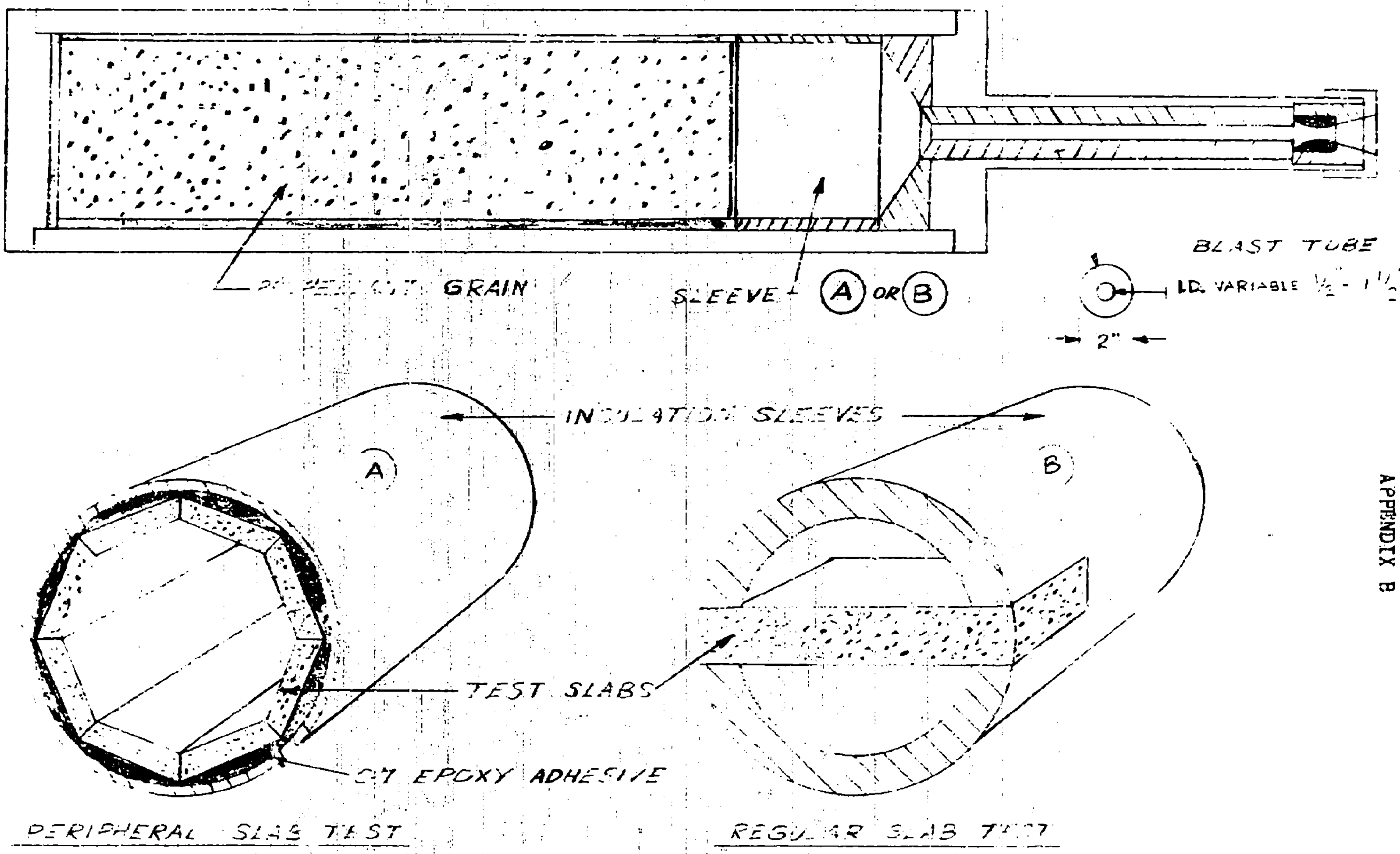


FIGURE - 11
SUBSCALE SOLID PROPELLANT TEST MOTOR
INSULATION EVALUATION

ALLEGHANY BALLISTICS LABORATORY

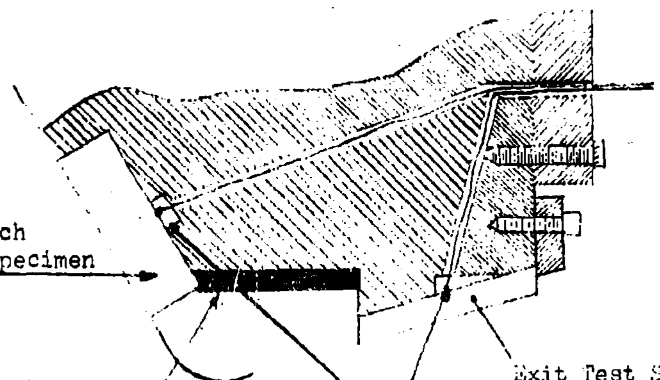


FIGURE - 12

Nozzle Section of Nine-Inch Test Motor for Approach and Exit Specimens

Nozzle Insulation Tests

ALLEGHANY BALLISTICS LABORATORY

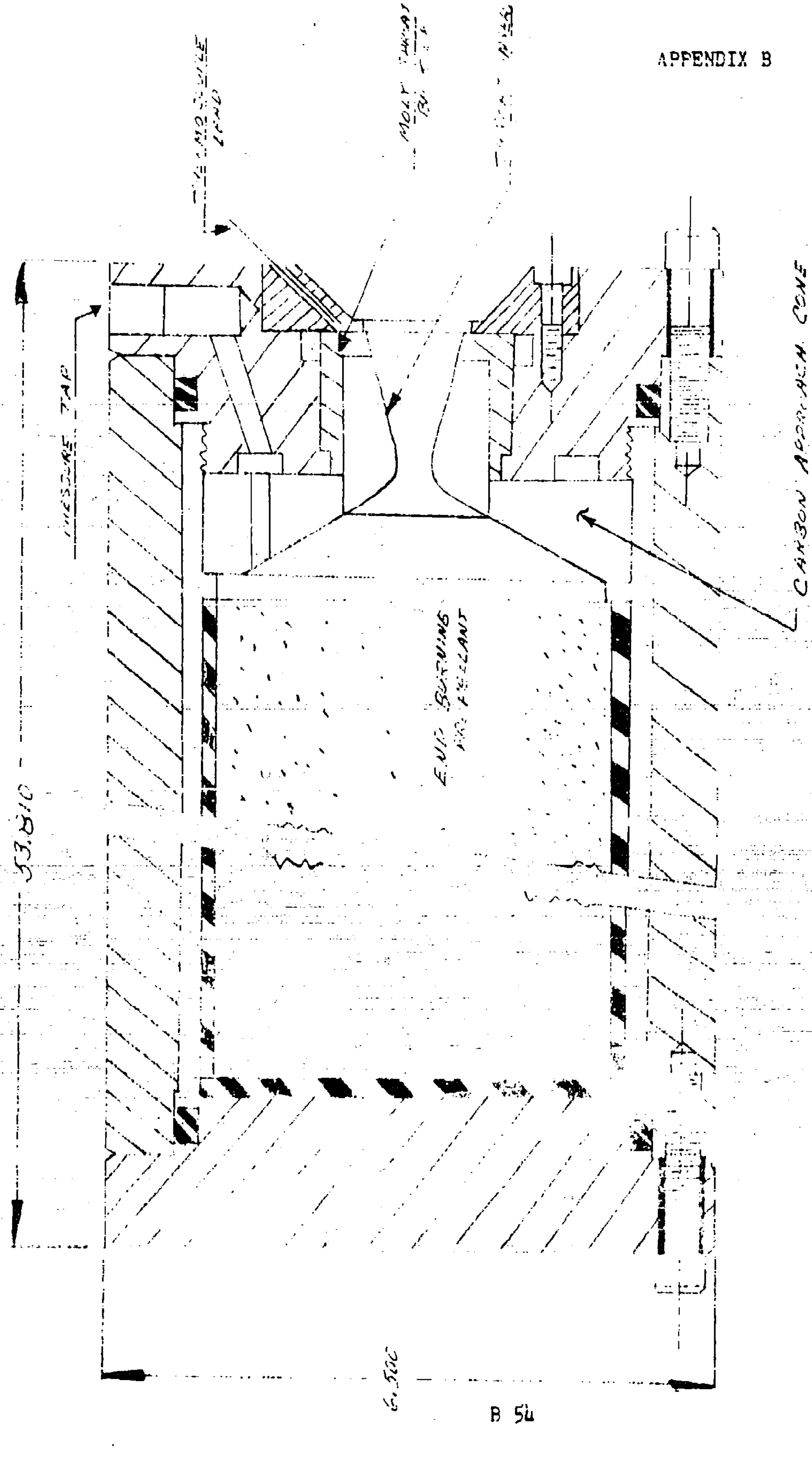


FIGURE - 13

SUBSCALE SOLID PROPELLANT 5" TEST MOTOR
NOZZLE INSERT MATERIAL EVALUATION

ALLEGHANY BALLISTICS LABORATORY

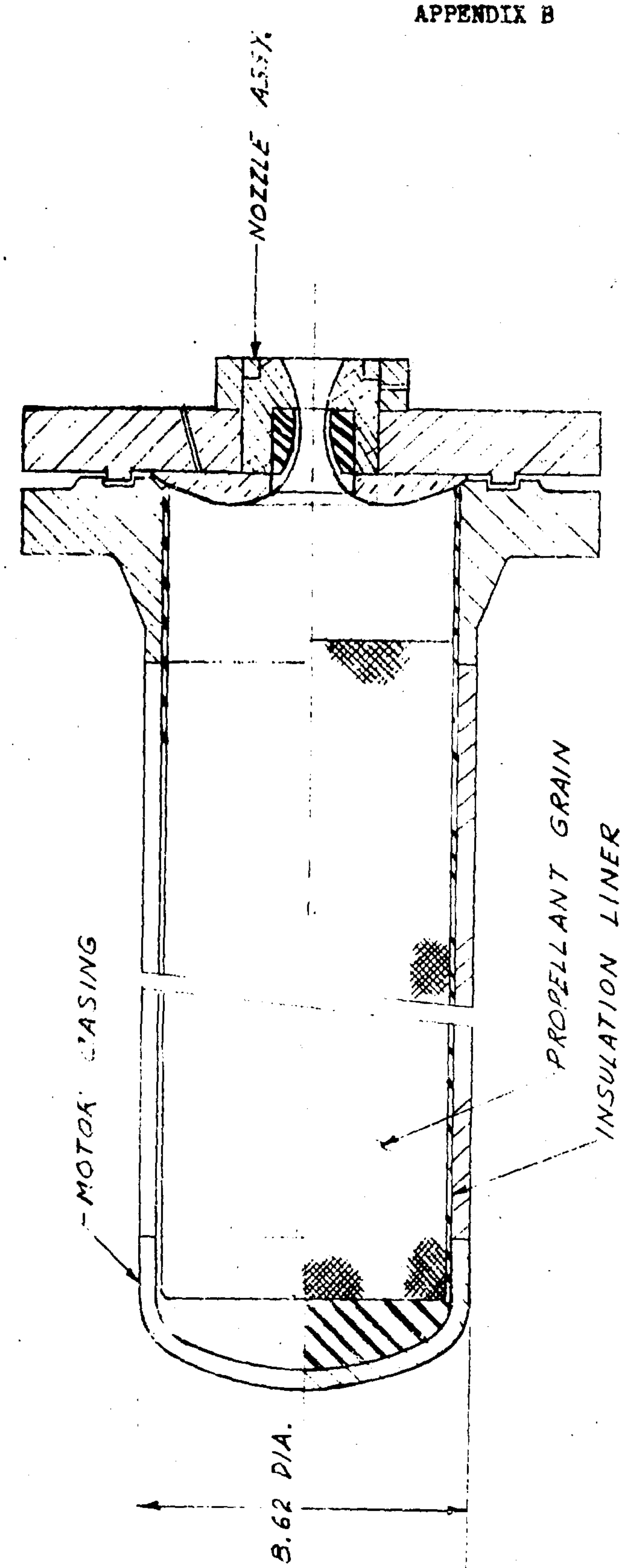


FIGURE - 14
MERM
MATERIAL EVALUATION ROCKET MOTOR

AEROJET GENERAL CORP.
(Sacto)

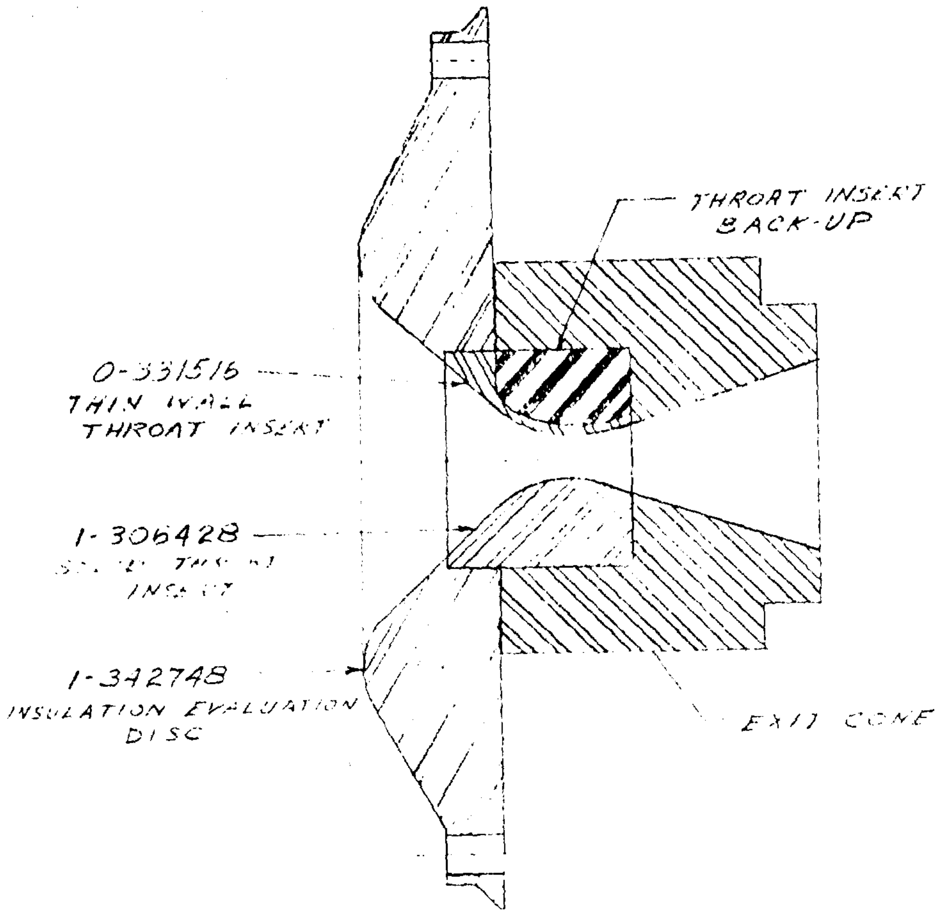
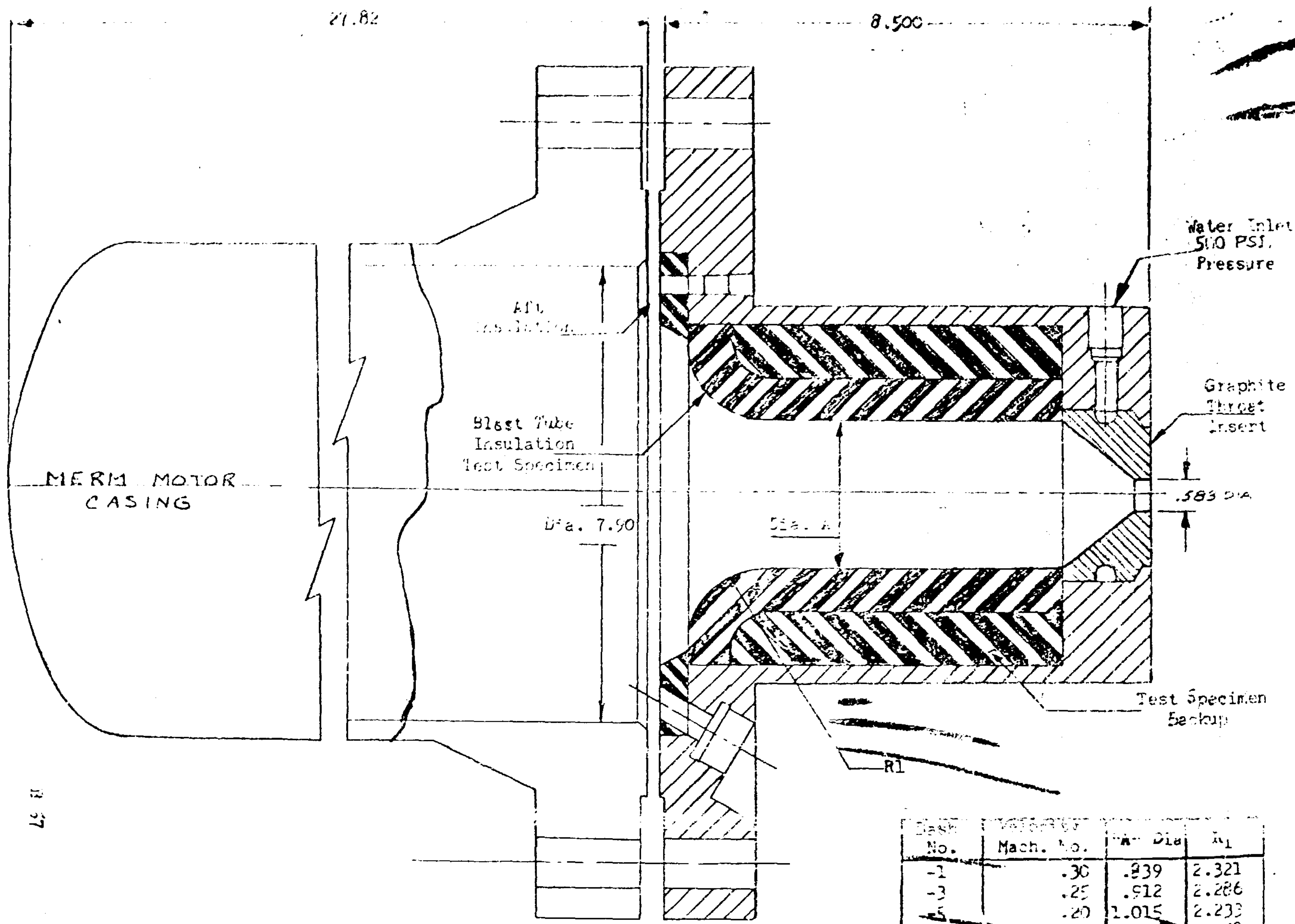


FIGURE - 15

-MERM-
NOZZLE ASSEMBLY

AEROJET GENERAL CORP.



Dash No.	Mach. No.	A* Dia	R_1
-1	.30	.939	2.321
-3	.25	.912	2.286
-5	.20	1.015	2.233
-7	[illegible]	1.165	2.158
-11	[illegible]	[illegible]	2.030
-13	.05	2.900	1.710
-15	.03	2.600	1.440

FIGURE - 16
-RITE-
ROCKET INSULATION TEST EVALUATION, MOTOR.
AEROJET GENERAL CORP. (SACTO.)