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RESEARCH MEMORANDUM

STATUS OF COMBUSTION RESEARCH ON HIGH-ENERGY FUELS FOR RAM JETS

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SUMMARY

To assist the research planning of government and industry, a review of the present status of research and development on high-energy fuels for ram-jet propulsion has been made. An examination of published information indicates that eleven organizations in this country have conducted or are conducting experimental investigations on the use of high-energy fuels in ram jets; eight of these organizations are currently active in the field. The materials included in these experiments are aluminum, boron, boron hydrides, carbon, coal and coal-light metal compositions, liquid hydrogen, and magnesium.

On the basis of heating value, fuel density, air specific impulse, and fuel-weight specific impulse certain substances offer certain performance advantages over conventional hydrocarbon fuels of the gasoline or kerosene type. These performance advantages accruing to a fuel are very much a function of the application intended and perfect generalizations can hardly be made. If beryllium, its compounds, and the undiscovered possibilities among compounds of light metals and hydrogen are not considered because of economic reasons, then, from thermodynamic considerations, the boron hydrides, hydrogen, boron carbide, and boron offer improved range or pay load for long-range, ram-jet powered vehicles. Magnesium, aluminum, and boron, in that order, offer higher thrusts from any tail-pipe burner or ram-jet engine of fixed air-handling capacity, or, conversely, permit the smallest ram-jet engines for a given thrust minus drag. Because these three fuels also have high bulk densities, they offer improved range or pay load for short-range ram-jet vehicles. Highest values of fuel-volume specific impulse belong to boron or boron carbide, carbon, and aluminum in that order. Where solid fuels are to be burned for rather short duration, the simplicity of combustion of solid blocks or fuel beds appears very attractive. Lack of certain thermodynamic data has made complete evaluation of all fuels difficult or impossible.

Although active work on high-energy fuels in the United States dates from late 1945, experimental work may still be considered in the early research stages. The combustion research has been in burners no larger than 6 inches in diameter. Pressed briquettes of carbon, coal, coal and light metals, aluminum, boron, and magnesium formulated with

binders and oxidants have been investigated as solid fuel beds installed in ram-jet combustors. Most of the experience with these beds has been with coal and with magnesium. Although some of the combustion tests of these fuel blocks have looked very promising, burning rates and the structural integrity of the fuel block have so far been inadequate for completing flight tests of research vehicles with these fuels.

Only limited exploratory tests have been achieved with methods of feeding solid fuels to ram-jet type combustors. Aluminum has been fed and burned as wire and powder, coal as powder and pellets, and magnesium as an oxidant-containing flare. All of these methods appear to require new concepts and invention for adequate storage and handling on an aircraft. Solid products of combustion have caused some difficulty in aluminum combustion.

Slurries or suspensions of aluminum, boron, and magnesium and some mixtures of these metals have been prepared in hydrocarbon fuel and burned in exploratory tests in small ram-jet type combustors. Of these, magnesium slurries in concentrations up to 60 percent by weight have received the most extensive evaluation. Excellent combustion characteristics were reported. More stable slurries of high metal concentration, and improved reliability in the fuel-feed equipment are among the research needs of this very promising technology.

Boron hydrides have received the very briefest of experimental combustion research. Diborane has been shown to burn easily and rapidly, but with the production of deposits. Pentaborane has not been sufficiently available. These promising fuels, although made of readily available elements, are fabulously expensive because of the elaborate chemistry required for their production.

In conclusion, there are fuels other than hydrocarbons that offer performance improvements for ram jets that can be obtained in no other way. Some of these fuels, although more expensive than hydrocarbons, are economically available. Much cheaper boron and boron-derived fuel is needed, however. Research directed at effective utilization of high-energy fuels is still in a sufficiently early stage that effort should not only continue along most of the present lines of attack, but also along such new lines of attack as appear promising.

INTRODUCTION

The interest in fuels other than hydrocarbons for jet-engine applications originates with the desire to extend thrust, range, or operating limits. As a consequence, there are a number of fuels of particular interest for use in ram-jet propulsion because of either the heat of combustion per pound, or the heat of combustion per cubic foot, or the flame temperature, or the anticipated combustion characteristics of the fuel. Fuels selected on one or more of these bases include light metals and light-metal compounds. Where solid fuels are concerned, the possibility of combustion of solid blocks or fuel beds appears attractive because of the simplicity achieved without a fuel-feed and control system. Research and development on the problem of burning some of these nonhydrocarbon fuels both as solid fuel beds and with flow feed systems has been undertaken by various organizations.

The intention of this report is to review the present status of research and development on high-energy fuels for ram-jet propulsion. Such a review will attempt to indicate the organizations working in this field, the scope and nature of their activities, and the general progress made to date. A limited discussion of the performance to be expected from the different fuels, together with the corresponding kinds of application suggested, will be included in this review. By indicating what information is now available on the utilization of high-energy fuels for ram jets, this status report may be of assistance to the research planning of government and industry. It should assist in indicating what fuels and what types of technology should receive intensive research and development.

According to published information since World War II, eleven organizations in this country and the Royal Aircraft Establishment in England have conducted or are conducting experimental investigations directly on the use of high-energy fuels in ram jets; eight of these organizations are currently active in the field. The materials included in these experiments are aluminum, boron, boron hydrides, carbon, coal and coal-light metal compositions, liquid hydrogen, and magnesium. Table I outlines the research and development programs that will be discussed in more detail in this report.

The German Luftfahrtforschung prior to 1945 investigated the application of finely powdered hard or soft coal as propellant for ram jets; some tests were also made with wood, charcoal, and coal containing an oxidant (reference 1). Several designs of fuel containers were studied. Combustion was demonstrated, and the thrust coefficients obtained with solid fuel were of the same order as with gaseous or liquid fuels. Fuel consumption was high owing, in part, to deterioration and loss of unburned fuel. This and similar research described by Dr. Alexander Lippisch, German aeronautical engineer, was in part instrumental in initiating research on coal-burning ram jets in the United States in late 1945 and early 1946 (references 2 to 4). In recognition of the high combustion temperatures and the high volumetric and gravimetric heats of combustion of metals, combustion of powdered aluminum, selected because of its availability and because it was believed to present combustion problems typical of other metals, was studied by the NACA and the RAE in 1946 and early 1947 (references 5 and 6); later, atomization of metal wire was studied and metal-impregnated plastic wire and metal-hydrocarbon pastes were tried as fuel feed systems by NACA. Although research on the preparation and properties of hydrides of boron has been active since 1912 under Stock in Germany and, more recently, under Professor H. I. Schlesinger and colleagues in this country (reference 7), combustion of diborane in a ram-jet type combustor was first reported by the Johns Hopkins University Applied Physics Laboratory in 1947; the material used was made available by the Bureau of Aeronautics (reference 5). General Electric Co. in 1947 reported on combustion of diborane in a torch (reference 8); NACA burned diborane in a ram-jet type combustor in 1950 (reference 9). Diborane has been studied at several laboratories as a rocket fuel. Ohio State University has burned hydrogen as a ram-jet fuel (reference 10) and has been developing pumps for liquid hydrogen (reference 11). Aerojet Engineering, Inc. also has developed a liquid hydrogen pump in conjunction with rocket research. In 1949 and 1950, Continental Aviation and Engineering Corp. as an Air Force contractor and Experiment, Inc. as a subcontractor investigated the use of cylindrical fuel briquettes of powdered metals, such as magnesium, with varying percentages of oxidizer and binder (references 12 and 13). Continental received some technical assistance from the Dow Chemical Company. More recently, Experiment, Inc. has undertaken the development of a 6-inch diameter metal fuel charge for a flight test missile of the "Bumblebee" project. Bureau of Mines has also investigated briquettes of metals with oxidizers and binders (reference 2). Experiment, Inc. also described "flare" injection of magnesium into a combustor (reference 13). In 1951 the NACA reported on the combustion of suspensions, or slurries, of up to 60 percent by weight of magnesium in jet fuel MIL-F-5624 (reference 14). The RAE had previously described the preparation of suspensions of aluminum powder in kerosene, but had never burned these suspensions (reference 15). The NACA has also experimented with the combustion of hydrocarbon suspensions or slurries of aluminum, aluminum and magnesium mixtures, boron, and boron and magnesium mixtures. North American Aviation, Los Angeles, California (reference 5) and Thompson Products, Inc., Cleveland, Ohio are known to be interested in the combustion of metallic fuels for ram jets, but their work is in a preliminary stage and almost no recorded information is available.

COMPARISON OF FUELS

Heating Values

As already discussed, initial selection of high-energy propellants is usually based either on calorific values, or on flame temperatures, or on anticipated combustion characteristics. Table II indicates pertinent physical and thermal properties of a number of materials selected for consideration as ram-jet fuels. The list is by no means exhaustive;

it is representative of the main possibilities in the field. The heats of combustion used are based on the oxides listed in the table. It is seen that, in order, hydrogen, diborane, pentaborane, beryllium, boron carbide, boron, and acetylene have higher heats of combustion on a weight basis than gasoline, with hydrogen having about 2.7 times as great a heating value on a weight basis. In order, boron carbide, boron, beryllium, titanium, aluminum, carbon, silicon, magnesium, pentaborane, 1-ethylnaphthalene, lithium hydride, and diborane have higher heats of combustion on a volume basis than gasoline, with boron carbide having almost 4.7 times as great a heating value on a volume basis. The heating values per pound of air burned for all of the substances listed are superior to gasoline, with the exception of carbon.

Heating value per unit weight and per unit volume. - As an approximation, the ultimate cruising range of a ram-jet aircraft depends directly on the heating value per unit weight of the fuel. The heating value on a weight basis is generally much more significant to long range than is the heating value on a volume basis. An illustration of this point is presented in figure 1 from an unpublished NACA analysis by Hugh M. Henneberry. In the analysis an aircraft of 150,000 pounds gross weight with a 10,000 pound pay load is considered for only the cruising regime. Every component of the aircraft is assumed to be specifically designed for each condition considered. The fuel was considered to be stored in the fuselage; stringer or structural weights to provide rigidity were varied with fuel weight and aircraft shape and size; a stainless-steel, 1/16-inch skin was assumed; structure to withstand 4-g acceleration was added; and enough engines, each of approximately 10 square feet cross-section area, were added to provide the thrusts required. An idealized air cycle was assumed, which is reasonable, because the engines operate at low fuel-air ratios for the conditions of the analysis. As fuel density decreases, the size and weight of the structure increase and the drag increases, shortening range. This influence of fuel density is seen to be greater at higher flight speeds and at lower altitudes. The heating value on a weight basis, nevertheless, overshadows the heating value on a volume basis for long range.

A generalization of the relative importance of fuel density for rocket-propelled vehicles also leads to the conclusion that propellant density is of reduced significance for long-range flight (reference 19). In reference 19, seven different analytical design studies by various investigators were used to obtain a correlation between range and a parameter Id^n, where I is the rocket specific impulse, d the propellant density, and n an exponent. Range usually varied with $(Id^n)^2$. As seen in figure 2, the exponent n approaches zero for increased ratios of fuel mass to empty mass, or for increased propellant loads.

Flight ranges greater than those obtainable with hydrocarbons thus will require fuels such as hydrogen, beryllium, boron, or boron carbide, boron hydrides, or acetylene. Although the use of heating values does not properly consider the thermodynamic state of the combustion products that would actually exist, an indication of the flight range available with fuels other than gasoline as compared to flight range with gasoline can be obtained from figure 1 and data in table II. For the hypothetical aircraft of figure 1 and a flight Mach number of 3.0 at 70,000 feet, the following flight ranges relative to gasoline are noted:

Fuel	Relative range
Beryllium	1.6
Diborane (-134.5° F)	1.6
Hydrogen (-423° F)	1.6
Boron carbide	1.5
Pentaborane	1.5
Boron	1.4
Acetylene (-119° F)	1.07
Gasoline	1.00
Carbon	.86
Aluminum	.82
Magnesium	.64
Titanium	.51

The analysis for figure 1 makes no provision for insulation or pressurization to contain such low boiling fuels as hydrogen, diborane, or acetylene. Further, the density of liquid hydrogen is so much lower than that of the other fuels that assumptions for aircraft structure that are applicable for most of the fuels may not be equally applicable for liquid hydrogen. Thus there is no assurance from the analysis that the thermodynamic promise for these fuels can be realized in practice. The Air Force, Project "Rand" considers from a preliminary analysis that, as far as liquid hydrogen is concerned, either the excessive insulation weight or the evaporation loss of hydrogen would be prohibitive in a long-range ram-jet vehicle.

The significance of heating value on a volume basis depends very much on the particular application. It is evident from the foregoing section that the drag induced by carrying fuel weight is more important to long range than the drag due to fuel storage. For very short-range flight, only small quantities of fuel are required and fuel density can not influence the total vehicle drag very much. A quantitative generalization of fuel selection on the basis of application, heating value, and density is sufficiently complex that other specific missions are best analyzed individually.

Where a high heating value based on volume is desired, fuels of interest include light metals such as aluminum, beryllium, boron, magnesium, and titanium; many hydrides of light metals; carbon, silicon, and boron carbide; and hydrocarbons such as 1-ethylnaphthalene. The NACA has prepared and examined the physical properties of several series of hydrocarbons of potentially greater heating value on a volume basis than conventional hydrocarbon fuels (references 20 to 25). These high-density hydrocarbons nearly always have less heat of combustion on a weight basis than does gasoline. It is to be noted that only beryllium, boron carbide, the boron hydrides, and boron are listed as superior to gasoline on both the basis of heating value per unit weight and heating value per unit volume.

Heating value per pound of air. - The heating value per pound of air burned is only a crude estimate of the temperatures, and therefore the thrusts, that can be obtained with the various fuels. Actually, the specific heats, physical states, heats of phase changes, and the dissociation energies of the combustion products must be considered in any calculation of combustion temperature and thrust, particularly where high combustion temperatures are concerned. These properties of the combustion products establish a limit to the combustion temperatures and thrusts that can be obtained. At high combustor-inlet temperatures, the maximum combustion temperature obtainable limits the outlet-to-inlet temperature ratio and thus limits thrust. For example, the maximum temperature ratio for a hydrocarbon fueled ram jet flying at a Mach number of 3.0 above 35,000 feet is 4, whereas at a Mach number of 4.0 the ratio is only about 2.7. For much higher flight speeds, fuels capable of higher combustion temperatures would appear to be required. In addition to this requirement for fuels for very high-speed ram jets, there are a number of instances where, for a given engine size, higher thrusts than those available from hydrocarbons may be desired or required, even without regard to specific fuel consumption, as for example, for short range ram-jet missiles, for second-stage boosting of missiles, for acceleration of ram jets, or for thrust augmentation of turbojet aircraft by tail-pipe burning during take-off or during superperformance. Although all of the substances listed in table II except carbon show greater heating value per pound of air than gasoline, yet as has been stated, the flame temperature, and the thrust and fuel-economy characteristics require a consideration of the nature of the combustion products.

Combustion Temperatures and Specific Impulse

Combustion-gas temperatures and composition for several fuels of interest have been calculated (references 26, 27, and 28) for an adiabatic constant-pressure combustion at 2 atmospheres and an initial temperature of 560° R by means of the matrix method of reference 29 and the thermodynamic data of reference 30. The calculations have thus far been limited to materials that according to heating values offer gains in performance and that also have a chance of becoming economically available, as will be discussed in a subsequent section of this report. The temperature data are summarized in figure 3. Octene-1 is analogous to gasoline. The inflections in the curves are due to the heats of fusion and vaporization of the metal oxides. The lack of sufficient thermal data on magnesium oxide precludes other than an estimate at high temperatures. The temperatures noted for stoichiometric fuel-air ratios are as follows:

Fuel	$^{\circ}$R
Magnesium	----
Aluminum	6160
Boron	5320
Pentaborane	4990
Diborane	4840
Hydrogen	4256
Octene-1	4180
Carbon	4173

It is apparent that the heat absorbed by phase changes and dissociation limits the maximum temperatures to values lower than those that the heating values might have indicated; for example, although the heating value per pound of air for aluminum is 2.6 times the value for gasoline, the temperature attained in the stoichiometric combustion of aluminum is only about 1.5 times that of gasoline. Nevertheless, the temperatures of figure 3 not only give a qualitative measure of the expected thrust, but also are indicative of the research problems to be anticipated in the fields of cooling and materials.

The air specific impulse and the fuel specific impulse are more appropriate indications of performance than is temperature (references 18 and 31). The air specific impulse is defined as the stream thrust, or total momentum (pressure times area plus mass flow times velocity), per unit of air mass flow with the exhaust stream at a Mach number of 1.0. The fuel-weight specific impulse is defined similarly as the thrust per unit fuel mass flow at the same condition; fuel-weight specific impulse is obviously the product of air specific impulse and air-fuel ratio. Air specific impulse may be translated into net internal thrust per pound of air at a given flight speed and altitude, first by adding any additional thrust derived by expanding from $\text{Mach} = 1$ to $\text{Mach} > 1$ at the nozzle exit (usually comparatively small for moderate expansion), and second by subtracting the stream thrust at the diffuser inlet. Thus, air specific impulse is indicative of the maximum thrust to be obtained with a particular fuel and from a limited air supply. Fuel specific impulse is indicative of the duration for which a given air specific impulse can be maintained with a limited fuel supply; it is a criterion of fuel economy.

Figure 4 summarizes calculations of air specific impulse and fuel-weight specific impulse for several fuels at an inlet-air temperature of 560° R and an inlet-air pressure of 2 atmospheres (references 26, 27, and 28). Additional values appear in reference 18. Maximum values of air specific impulse shown correspond to stoichiometric fuel-air ratios except for octene-1. It is noted that for values of air specific impulse below about 172 pounds thrust per pound air per second, the maximum for octene-1 (or gasoline), better fuel economy and thus potentially longer flight ranges may be obtained with hydrogen, the boron hydrides, and below an air specific impulse of 142, with boron. For example, at the value of air specific impulse of 110, corresponding to a temperature rise of about 1540° F for gasoline, the fuel-weight specific impulse, and thus conceivably the flight range, of the substances studied in references 26, 27, and 28 is in the following order:

Fuel	Fuel-weight specific impulse ((lb)(sec)/lb fuel)
Hydrogen	14,500
Diborane	8,400
Pentaborane	7,800
Boron	6,700
Octene-1	5,500
Carbon	3,950
Aluminum	3,600
Magnesium	2,950

The order of this list is in general agreement with the list of relative range compiled from figure 1 and table II. Presumably, beryllium would also give greater fuel economy and thus longer range than gasoline as might certain other compounds of light metals and hydrogen not discussed in this report.

Although aluminum and magnesium have consistently lower fuel-weight specific impulse, these fuels as well as certain others can give higher values of air specific impulse than is possible with hydrocarbons, primarily because of the greater total-temperature ratios together with significant increases in exhaust mass. The following list shows the air specific impulse theoretically available at stoichiometric fuel-air ratios with combustion inlet air at 2 atmospheres and 560° R for the fuels from figure 4:

Fuel	Air specific impulse ((lb)(sec)/lb air)
Magnesium	224 (est.)
Aluminum	212
Pentaborane	186
Boron	186
Diborane	185
Hydrogen	180
Octene-1	170
Carbon	165

The higher values of air specific impulse obtained with magnesium, aluminum, or other fuels will, compared to gasoline, correspond to very appreciable percentage gains in engine thrust or in thrust minus drag. These high values of air specific impulse also permit the smallest engines for a given thrust minus drag. Because of the high drag resulting from fixed-geometry ram-jet engines operating at other than the design flight Mach number, fuels permitting small engines appear desirable for short-range applications where flight speed and altitude vary through much of the mission.

The values of fuel-volume specific impulse (fuel-weight specific impulse times fuel density) may be compared at the rather high value of 160 pounds thrust per pound air per second for air specific impulse, thus:

Fuel	Fuel-volume specific impulse ((lb)(sec)/cu ft fuel)
Boron	380,000
Carbon	310,000
Aluminum	303,000
Magnesium	168,000
Octene-1	130,000
Pentaborane	103,000
Diborane (-134.5° F)	100,000
Hydrogen (-423° F)	22,000

For applications requiring fuels capable of high fuel-volume specific impulse, boron, carbon, and aluminum would clearly be preferred.

One way in which metallic or other solid fuels might be stowed and fed to an engine on an aircraft is as a suspension, or slurry, in a carrier such as a hydrocarbon. Hence, it is desired to evaluate the potential performance of such slurries. Figure 5 (from references 26, 27, and 28) presents the effect on air specific impulse of varying the concentration of metal in octene-1 suspensions at an over-all stoichiometric fuel-air ratio. It is noted that, unless only the metal in the slurry is burned, rather high metal concentrations by weight are required if an appreciable part of the greater air specific impulse available with the pure metal is to be realized. Figure 6 presents the effect of metal concentration on fuel-weight specific impulse from the same references, and figure 7 is a cross-plot of figures 5 and 6 with curves for the base fuels and slurries for boron and magnesium in octene-1. The curves for the base fuels represent variable stoichiometric fraction; the curves for the slurries represent a fixed stoichiometric fraction of 1, but variable metal-in-octene-1 concentrations. The data for aluminum slurries are so close to the data for magnesium slurries that they were omitted here for clarity. It is seen that, for any value of air specific impulse intermediate to the maximum obtainable with hydrocarbon and the maximum obtainable with metal alone, a higher value of fuel-weight specific impulse is obtained with a metal slurry than with the metal alone. Figures 5, 6, and 7 assume that both the metal and the hydrocarbon carried burn to thermodynamic equilibrium. If only the metal in a slurry is burned in order to realize high thrust, the unburned carrier will reduce the fuel-weight specific impulse.

Availability of Fuels

In the selection of fuels for intensive research and development, the question of general availability of the fuel or the raw materials for it must be considered.

Of the fuels previously discussed, hydrocarbon fuels and coal are certainly available in the quantities that would permit fueling ram jets without embarrassment to other uses of these fuels. Hydrogen also cannot be considered critical, although there would be a need for liquefying machinery if liquid hydrogen were to be considered for intensive research and development. The technical difficulties associated with utilizing liquid hydrogen because of its low boiling point and because of the heat released by the ortho-para conversion at liquid-hydrogen temperatures need no further discussion.

Of the metals, both aluminum and magnesium may be considered as available in sufficient quantity for use as a special ram-jet fuel. After oxygen and silicon, aluminum is the most abundant element in the earth's crust; however, its production is moderately expensive because (1) pure aluminum oxide must be prepared from the naturally occurring bauxite; and (2) about 9 to 10 kilowatt-hours of electricity per pound of aluminum are required (reference 32). Currently, aluminum is quoted at 18 cents a pound (reference 33). In 1944 the projected annual aluminum production capacity of the United States was reported by the U. S. Bureau of Mines to be 1,172,000 short tons, and in that year 776,000 tons of new metal were produced. High grade, low-silicon bauxite, vital to economical aluminum production, is considered strategic and critical material. Bauxite amounting to 14,169,000 tons was mined from January 1940 to January 1945. Today, the United States has very low reserves of bauxite of the quality used as ore before World War II. Major deposits are in Brazil, Surinam, British Guiana, Hungary, Haiti, and Jamaica. United States resources in lower grade bauxite and clay are enormous. Reserves of bauxitic and high alumina clays in the United States were estimated at 3 billion tons in 1944 (reference 34). Submarginal and speculative material is plentiful (reference 32). Conceivably, then, aluminum, although available, might not become a cheap fuel for ram jets as long as the increased cost of processing lower grade bauxite is a controlling factor.

Magnesium is the third most abundant of the engineering metals, being surpassed only by aluminum and iron. The supply of raw materials, - sea water, brines, and salt deposits - is virtually inexhaustible. In 1944 a capacity of 300,000 tons per year of metal was reported for the country, and 168,000 tons were produced that year; by the end of 1944 the magnesium supply was so plentiful that production was down to 15 percent of capacity. Seventy percent of the magnesium came from electrolysis of magnesium chloride, 22 percent from the reduction of dolomite and ferrosilicon, and 8 percent from reduction of magnesia with carbon in 1944 (reference 32). Currently, magnesium is quoted at $24\frac{1}{2}$ cents per pound (reference 33). Although only about one-fourth the production capacity of aluminum exists for magnesium, because of the more favorable raw-material situation and the less stringent demands for other uses, magnesium is in a good position as a ram-jet fuel.

Beryllium is a valuable nonferrous metal used for alloying and in atomic-energy work. Production of beryllium and its alloys is one of the most difficult procedures in metallurgy. Its ore, beryl, is scarce. In 1943, a little over 5000 metric tons were produced in the world, mostly from Brazil, India, and Argentina (reference 32). United States consumption of beryl ore was only 1735 tons in 1947, based mostly on imports (reference 35). Thus beryllium or its compounds, however attractive performance-wise, should not be considered as a ram-jet fuel.

Boron metal itself is not prepared in large quantities for any purpose. In 1947, the United States used 147 tons of ferro-boron containing 13 tons of boron as alloying material. The new boron-alloy steels use only 0.002 percent boron (reference 36). Extensive deposits of boron-containing salts, however, occur in saline lakes notably in California, but also in Chile, Tibet, Peru, and Canada. These salts are sodium borates (e.g., borax, rasovite) and calcium borate (e.g., colemanite). Apparent consumption of boron minerals in 1947 in the United States was 416,200 tons for many uses including soap, glass, glazes, and water softening. About 17 percent of the United States output was exported. Currently, borax is quoted at $33.25 per ton (reference 33). According to oral information from a United States producer of metallic, amorphous boron, the basic mineral from which he produces boron presently costs \$1.00 per pound of boron, the 3 pounds of coarse magnesium used for the reduction costs \$0.65 per pound, and the minimum cost foreseen for boron produced this way is \$6.00 per pound. The current market price of amorphous boron is \$12.00. Thus, although fairly large sources of supply for boron exist, it appears to be a very expensive fuel. Improved technology in boron or boron carbide production to lower the price of the fuel is needed. The boron hydrides, for example, diborane and pentaborane, so very superior for long-range ram-jet propulsion, are presently made in pilot-plant batches by rather elaborate chemistry; the resulting selling prices are in the hundreds of dollars per pound. This general statement is also true for compounds of boron, hydrogen, and other light metals, such as aluminum borohydride and lithium borohydride. Because of the availability of boron and hydrogen as starting materials, boron hydrides should not be discarded from consideration for fueling ram jets, but unless very radical advances are made in the technology of producing them they cannot reasonably be used.

Thus, on the basis of availability of fuels that offer improved performance in one respect or another over the conventional hydrocarbons, there are liquid hydrogen, carbon or coal, aluminum, magnesium, and, just possibly, boron, boron carbide, or hydrides of boron or other light metals. The boron-containing fuels require radical advances in the technology of their production. All of these fuels, except boron carbide, have been used in combustion experiments.

EXPERIMENTAL COMBUSTION STUDIES ON SOLID-BED SYSTEMS

Bureau of Mines - Carbonaceous Fuels

Since 1946 the use of solid fuels has been under investigation at the Bureau of Mines laboratories at Pittsburgh, Pennsylvania (reference 2) under the sponsorship of the Navy, Bureau of Aeronautics. The work has included investigation of solid briquettes and continuous feed of pulverized coal as powder and as pellets. The work on solid briquettes will be discussed in this section and the continuous-feed systems will be considered in another section of this report. The purpose of the investigation has been to develop a solid fuel for a short-range ram-jet application.

<u>Apparatus</u>. - Most of the combustion of solid carbonaceous fuels has been conducted in a test facility provided with a blower that delivers air at the rate of 3300 cubic feet per minute at a pressure of 20 pounds per square inch absolute. The apparatus is instrumented to measure exhaust-gas temperatures, to obtain exhaust-gas samples, and to measure thrust. The major part of the development work has been conducted with a combustion chamber 6 inches in diameter and 6 feet long.

In 1950 facilities were installed to provide a larger quantity of air delivered at higher pressures. At the present time air can be provided at the rate of 5 pounds per second at a pressure of 20 pounds per square inch absolute and 3 pounds per second at a pressure of 35 pounds per square inch absolute. Facilities are under construction at the present time to double the air supply.

Fuels. - The initial work on solid briquettes was done with lignites and coals. During progress of the development, it was learned that coal mixed with metals and a slight amount of oxidizer seemed to give the most satisfactory combustion properties. The fuel components are prepared as powders that will pass through a 200-mesh screen. The powders are thoroughly mixed in the dry state and then mixed with a liquid binder. This mixture is pressed at a pressure of about 4000 pounds per square inch. After curing, the briquettes apparently have satisfactory physical properties.

Investigation of binders included asphalt, pitch, boiled linseed oil, thermosetting resins, latex, and plasticized nitrocellulose. The nitrocellulose is plasticized with an equal weight of dibutylphthalate.

A few of the fuel compositions that have been investigated are shown in table III. The types of coal found to be most satisfactory for ram-jet fuels are Bituminous A type coals such as Pittsburgh Seam, Pocahontas, and Bell Coal from Kentucky. The shapes of the briquettes most extensively investigated include a cylinder of 6-inch outside diameter and $4\frac{1}{2}$-inch inside diameter, and a solid cylinder 6 inches in diameter in which seven 1-inch holes are bored in a symmetrical fashion as shown in figure 8. The length of briquette has been varied but a length of 36 inches has been investigated most extensively.

A third type of briquette was used in some of the investigations. Cylinders were made with a 3.3-inch outside diameter and a 1.75-inch inside diameter. They were placed in a combustor 10 inches in diameter in the arrangement shown in figure 8(b). This arrangement resulted in a void space of 45 percent.

Ignition. - Early work indicated that ignition of carbonaceous fuels for a ram-jet application was very difficult to accomplish and a large amount of effort has been required in this phase of the development.

The composition of a satisfactory igniter is as follows:

Ingredient	Percent
Silicon	20.0
Potassium nitrate	26.9
Carbon	3.1
Aluminum	25.7
Copper sulfate	24.3

The ingredients are all reduced to particle sizes that will pass through a 200-mesh screen. They are thoroughly mixed in the dry state and pressed at a pressure of 4000 pounds per square inch into an iron tube of the desired diameter. In operation, the igniter is placed approximately 6 inches upstream of the fuel bed and the igniter is initiated on the downstream end by a black-powder squib, which in turn is ignited electrically. This igniter system is capable of igniting in less than 1 second a carbonaceous fuel, such as mixtures D, E, G, and H shown in table III. Some ignitions have been accomplished at air velocities of approximately 200 feet per second.

The composition of the fuel as well as the composition of the igniter influences the rate of ignition. Investigations have shown that sodium nitrate or sulfur is required and that boron in the fuel and igniter reduces the time required for ignition.

Experimental results. - Most of the data obtained in the combustion research on the carbonaceous fuels have been expressed as plots of temperature attained during combustion against time of burning. Such a plot is shown in figure 9. Exhaust-gas temperatures were obtained by use of platinum - platinum, 10-percent rhodium thermocouples, and flame temperatures were calculated from the results of exhaust-gas analysis. Both temperature curves are plotted in figure 9. The data indicate high temperatures and rapid and uniform burning of the solid fuel. The results indicate a great deal has been accomplished in alleviating the erratic and nonuniform burning first encountered in this investigation. This advance may be attributed in large part to the use of a small quantity of an oxidant, such as sodium nitrate, and the use of metals as part of the fuel charge. Apparently, the fuel charge burns satisfactorily at air velocities up to 218 feet per second at a pressure of 20 pounds per square inch absolute.

The effect of pressure on the combustion of carbonaceous fuels has been studied briefly and some results are shown in figure 10. Fuel charges were burned at pressures of 20 and 35 pounds per square inch at two air flows; namely, 2.4 and 3.0 pounds per second. Figure 10(a) shows results plotted as temperature against time for an air flow of 2.4 pounds per second. In this case burning was more satisfactory at a pressure of 35 pounds per square inch absolute. In figure 10(b) the data are shown for an air flow of 3.0 pounds per second. In this case the burning was more satisfactory at 20 pounds per square inch absolute than at 35 pounds per square inch absolute. The data indicate the need for additional information on the effect of air pressure and velocity on the burning of carbonaceous fuels.

Unfortunately, combustion efficiencies for recent formulations of carbonaceous fuels are not reported in reference 2. In the early part of the work, as much as 33 percent of the fuel charge would be blown out of the combustor as unburned material. It is not known whether this condition has been corrected.

Bureau of Mines - Metallic Fuels

The investigators at the Bureau of Mines have studied the combustion of metallic briquettes as ram-jet fuels. Most of the investigations have been conducted in a 3.5-inch combustor with air facilities described under the section on Carbonaceous Fuels.

Some of the more successful fuel compositions that have been investigated are listed in table IV.

The ingredients for the fuel mixtures are pressed as dry powders, at 4000 pounds per square inch, into a magnesium or iron casing as illustrated in figure 11. The charge is cemented to the casing but no binder is used for the main fuel charge. It is anticipated that such a fuel charge could be used in a ram-jet configuration as shown in figure 12. The fuel charge is ignited at the downstream end with the electric squib-black powder igniter mentioned under Carbonaceous Fuels. The charge burns as a cigarette from the downstream to the upstream end.

The performance of one of the fuels, designated MFM-31, is illustrated in figure 13. Jet thrust is plotted against time in seconds for a simulated flight Mach number of 1.05. The total time was 10 seconds. About 4 seconds were required for the unit to deliver maximum thrust, which was maintained for about 4 seconds before the thrust decreased. The combustion efficiency in this particular test was 25 percent. At a simulated Mach number of 1.3, however, combustion efficiencies of 60 to 65 percent have been obtained.

The performance of some of the Bureau of Mines metallic fuels has been determined at the NACA Wallops Island Station. The experiments were conducted in a ram jet mounted in a 8-inch-diameter free jet at Mach numbers of 1.7 and 2.2 at standard sea-level static pressure with an air stagnation temperature of 310° F. The engine had an open-nose normal-shock inlet 3.27 inches in diameter, expanding to a combustion-chamber diameter of $6\frac{1}{2}$ inches. Exhaust discharge pressure was 1 atmosphere. The fuel charges were $4\frac{1}{2}$ inches in diameter and $8\frac{1}{2}$ inches long and were used in combustion chambers 36 inches and 48 inches long. They were mounted on an inner body as illustrated in figure 12. The results of the tests are tabulated as follows:

Mach number	Length of combustion chamber (in.)	Fuel type	Average air specific impulse ((lb)(sec)/lb air)	Burning time (sec)	Weight of fuel (lb)
2.2	36	MFM-20	96	2.8	6.33
2.2	48	MFM-20	107	3.05	6.24
2.2	36	MFM-35	89	4.15	5.14
1.7	48	MFM-31	86	5.65	6.73

The burning rate of the fuel charge was about twice as fast in these tests as had been experienced in the Bureau of Mines tests.

The type of burning obtained with the fuels is indicated in figure 14 where air specific impulse is plotted against time in seconds. The somewhat erratic nature of the curve indicates that probably pieces of the propellant broke off the solid charge during the experiment. Motion pictures taken during NACA tests indicated a considerable amount of afterburning in all the runs, which accounts for a low air specific impulse. Apparently the afterburning is due to particles of fuel being removed from the fuel bed and burning outside the ram jet. The combustion efficiencies were calculated to be 50 percent. The low specific impulse in addition to the short burning time gave a total impulse too small for a ram-jet application.

The investigations of metallic fuels at the Bureau of Mines to date indicate promise of good specific impulse. However, investigations must now be conducted at higher inlet-air temperatures, pressures, and velocities than previously investigated in order to evaluate properly the potentialities of solid metallic fuels for ram-jet application. A particularly pertinent point is to know whether burning rate will vary as inlet-air pressure, temperature, and velocity are varied, as encountered in flight. If the burning rate varies with inlet conditions, it might be difficult to provide constant thrust with solid fuels. One apparent solution to this problem is indicated by research at the Bureau of Mines and at Continental Aviation. Their investigations indicate that solid fuels packed to a high density have slower burning rates than fuels packed to a lower density. It may be possible by preparing fuel charges of varying density to maintain constant burning rate with varying inlet-air conditions.

In addition to controlling the burning rate, it will be necessary to increase the total time of burning for most ram-jet applications. The combustion-chamber length is an additional factor that must be investigated in order to develop a practical fuel charge. Most of the burning work at the Bureau of Mines has been conducted in a combustion chamber that is 6 feet in length. Obviously for ram-jet application it is desirable to reduce the length of the combustion chamber as much as possible.

Continental Aviation and Engineering Corporation - Magnesium

The greatest portion of the combustion research at Continental was carried out on a 6-inch-diameter burner mounted on a thrust stand (reference 12). Air was available in quantities up to 10 pounds per second at pressures up to approximately 36 pounds per square inch absolute. Exploratory combustion work was conducted on a 2-inch-diameter burner with air pressure available up to 90 pounds per square inch absolute.

Fuels. - The fuel composition most extensively investigated consisted of 93-percent atomized magnesium, particle size below 325-mesh; 5-percent sodium nitrate, particle size below 70-mesh; and 2-percent linseed oil as a binder. Rubber cement was later found to be a better binder than linseed oil. Most of the investigation was conducted with fuels fabricated in the form of a hollow cylinder with a 6-inch outside diameter and a 4-inch inside diameter. The fuel charges were fabricated by mixing the fuel ingredients with acetone and molding at 4000 pounds per square inch. After baking for 8 hours in a steam oven at 150° F, the 4-inch long briquettes, together with the upstream igniter, were glued together with cellulose cement to form one long charge, usually 24 inches. This fuel charge was then coated with phenolic cement and inserted into a metal or cardboard liner.

Igniter. - The igniter used most frequently consisted of 35-percent magnesium powder, 35-percent barium nitrate, and 30-percent nitrocellulose cement. On the upstream surface of the igniter, an electric squib was bonded by a paste of black powder in nitrocellulose cement.

Experimental results. - Typical results of burning solid fuels with various quantities of sodium nitrate are shown in figure 15, where air specific impulse is plotted against equivalence ratio, or stoichiometric fraction. The conditions of the tests are shown on the figure. The combustor used for these tests had a straight tail pipe so that L^* was defined as the length of the tail pipe plus half the fuel charge. The figure shows the air specific impulse to be high over quite a range of equivalence ratios. For comparison purposes, gasoline was stated in reference 12 to have a theoretical air specific impulse of 175 at an equivalence ratio of 1. The effect of tail-pipe length was studied and it was found that increasing the tail-pipe length gave increased specific impulse, which indicates that combustion occurred not only on the surface of the fuel charge but also in the tail pipe downstream of the charge.

The work at Continental included an investigation of some of the factors that influence burning rate. The concentration of sodium nitrate in the propellant mixture was varied from 0 to 12.5 percent, and it was shown that burning rates increased as the concentration of oxidizer increased, and that burning rate was only slightly a function of equivalence ratio.

The effect of air mass flow was also investigated by both Continental and Experiment Incorporated. Air mass flow was varied by changing critical flow orifices in the air supply line, and combustion-chamber pressure was controlled by varying the size of the exhaust nozzle. Thus combustion-chamber pressure and mass flow were varied independently. Some results are shown in figure 16, where radial burning rate in inches per minute is plotted against air mass flow per unit mean air passage area at different pressures. The data show that burning rate is a direct function of air flow per unit area for the pressures studied.

In reference 12, it is pointed out that the data in figure 16 indicate that the briquette-type burner is an approximately constant fuel-air ratio device and thus would be self metering over a range of flight Mach numbers and altitudes.

The performance of some Continental Aviation solid fuels has been determined at the NACA Wallops Island Station. The engine used in the tests had an open-nose normal-shock inlet 3.27 inches in diameter, expanding in a diffuser to a $6\frac{1}{2}$-inch-diameter combustion chamber. A combustion-chamber shell length of $43\frac{1}{8}$ inches was used. The fuel charges were fabricated into hollow cylinders, with an outside diameter of $6\frac{1}{2}$ inches and an inside diameter of $4\frac{1}{2}$ inches. These charges were attached to the combustion-chamber wall. Tests were conducted in an 8-inch-diameter free jet at Mach numbers of 1.6 and 2.2 at standard sea-level static pressure. Air stagnation temperature varied from 679° to 711° R and exhaust was to atmospheric pressure.

Fuel compositions were varied to allow various concentrations of oxidizer from 5- to $12\frac{1}{2}$-percent sodium nitrate with a corresponding 93- to $85\frac{1}{2}$-percent magnesium with 2-percent linseed-oil binder.

Two exhaust nozzles were used in these runs. One was a $5\frac{1}{2}$-inch-diameter nonexpanding nozzle and the other was a 6-inch-diameter nonexpanding nozzle.

The value of L^* was defined in these tests as one-half the length of the fuel charge added to the length of the tail pipe and multiplied by the ratio of engine cross-sectional area to nozzle-exit area.

The conditions of the tests and the average specific impulses obtained are shown in table V. A plot of air specific impulse against time obtained with one oxidant concentration is shown in figure 17. The results indicate that the specific impulse was somewhat erratic, probably due to fuel blowing out of the combustor before burning was complete.

In figure 18 the average air specific impulses for the eight tests shown in table V are plotted as a function of equivalence ratio.

Comparison of the data in figure 18 with those in figure 15 indicates that the maximum values of specific impulse obtained by the NACA agree fairly well with the values shown in figure 15. However, the average values of air specific impulse obtained at the NACA are lower than these maximum values. It is to be noted that the L^* used in the Continental tests is considerably larger than those used in the NACA tests. It is possible that in the NACA tests some of the solid fuel was blown from the combustor before burning was complete.

The Continental fuel was flight tested by the Air Force but with limited results because part of the fuel was lost from the ram jet owing to a failure of the cement between the fuel charge and the burner wall. It has been suggested that a retainer ring at the end of the fuel bed would be effective in keeping the fuel inside the ram jet.

In the present state of development of solid-fuel beds, the problem of keeping the burning fuel inside the ram jet during high-speed flight seems to be of major importance. Improved binders are being investigated at the present time by the Continental Aviation and Engineering Corporation.

Continental Aviation and Engineering Corporation - Other Solids

Continental did exploratory work on boron and burned a number of mixtures of boron and magnesium with sodium nitrate and a binder. Boron concentrations were varied from 18 to 93 percent. Satisfactory burning was obtained with several compositions but a briquette with satisfactory physical properties was not obtained.

They also conducted very brief exploratory work on briquettes containing aluminum and briquettes of naphthalene. Both materials seemed worthy of further investigation. Naphthalene was of particular interest because of its low cost.

Experiment Incorporated

The initial work on solid fuels at Experiment Incorporated was done under sponsorship of Continental Aviation and Engineering Corporation and is now being continued under sponsorship of the Bumblebee Project.

Apparatus. - A large part of the evaluation of solid fuels was done on a 2-inch-diameter ram jet installed on a thrust stand. The installation was instrumented in order to obtain pertinent pressure and mass-flow data so that thrusts could also be calculated. The burner could be operated over a range of pressures from 0.4 to 4 atmospheres. In addition to the 2-inch ram-jet burner, a burner was developed for the injection of vaporized and atomized magnesium into a ram-jet combustion chamber by means of burning a flare. A schematic drawing of such a burner is shown in figure 19. The flare burns at a constant rate and thereby feeds magnesium into the air stream at a constant rate.

Fuel composition. - The composition of the fuel used in the flares was 84-percent magnesium, 15-percent sodium nitrate, and 1-percent linseed oil.

The fuel composition used for a large number of burning tests in the conventional type ram jet consisted of 90.5-percent magnesium, 7.5-percent sodium nitrate, and 2-percent linseed oil. The fuel was molded into hollow cylinders with an outside diameter of 2 inches and an inside diameter of 1 inch. The cylinders were 6 inches in length.

Binders. - The binders that were investigated included boiled linseed oil, dehydrated castor oil, tung oil, soy bean oil, Oticica oil, and nitrocellulose. Boiled linseed oil and nitrocellulose were about equally satisfactory but inasmuch as linseed oil was safer and easier to handle than nitrocellulose, the linseed oil was used in most of the experimental work.

Ignition. - Several igniter compositions were compounded with barium nitrate and aluminum or magnesium as the chief ingredients. A typical composition was 33 parts of barium nitrate, 62 parts of magnesium, and 5 parts of linseed oil.

Fuel was ignited when the air velocity over the charge was as high as 1000 feet per second. Full thrust was obtained within 0.2 second after burning started.

Experimental results. - Many experiments were conducted on the burning characteristics of solid fuel in both the conventional-type combustor and in the flare-type combustor. The air specific impulses obtained with the flare-type combustor were determined from 0.4 to 3 atmospheres. The results indicated no effect of pressure. Typical results indicated that, at an equivalence ratio of 0.3, the measured air specific impulse was about 75 percent of the theoretical value. At an equivalence ratio of 1.0, the measured value was about 88 percent of theoretical.

The effect of air mass flow and pressure on burning time and specific impulse was also determined on the conventional 2-inch burner. The air mass flow was varied by changing critical flow orifices in the inlet air system, and combustion-chamber pressure was changed by changing the area of the exhaust nozzle. The burning rate increased with increasing air mass flow as shown in figure 16. The burning rate did not seem to be influenced by changes in pressure over the range investigated, which was approximately 27 to 55 pounds per square inch absolute.

Another variable that influenced the burning rate was the density of the fuel charge. A mixture of 83-percent magnesium, 15-percent sodium nitrate and 2-percent castor oil with a density of 0.76 gave a burning rate of 43 inches per minute. The same material at a density of 1.26 gave a burning rate of 22 inches per minute. The experiments mentioned above were conducted on solid cylinders of material with cigarette-type burning.

One of the burner configurational variables examined was that of tail-pipe length. A definite increase in air specific impulse was obtained when the tail-pipe length was increased from 4 inches to 24 inches, but there was no further increase in air specific impulse when the tail-pipe length was increased to 8 feet. This information indicates that some of the burning of the fuel must occur downstream of the solid-fuel bed.

The data indicate that Experiment Incorporated has been very successful in its preliminary work on the burning of fuels compounded with magnesium. Of particular significance are their data indicating that burning rate of solid fuels is not influenced by combustion-chamber pressure and that burning rate is a linear function of air mass flow.

Massachusetts Institute of Technology - Carbonaceous Fuel

Ram-jet combustion. - Solid fuel briquettes have been prepared at the Massachusetts Institute of Technology from powdered Pocahontas coal mixed with nitrocellulose and dibutylphthalate as binding materials (reference 3). After consideration of various mixtures the best composition was determined to be 80-percent coal, 10-percent nitrocellulose, and 10-percent dibutylphthalate. One fuel bed used for combustion investigations consisted of five slabs, 12 inches by $2\frac{1}{2}$ inches by $\frac{1}{4}$ inch molded at 3300 pounds per square inch from the composition described. The slabs were arranged parallel and spaced approximately $\frac{1}{4}$ inch apart. Ignition was accomplished by burning strips of thermite $\frac{1}{8}$ by 3 inches at the downstream end of the combustor. Results of burning tests reported in March 1950 (reference 3) and June 1950 (reference 38) indicate maximum fuel-bed temperatures of about 2400° F and maximum gas temperatures of 2400° F measured 7 inches downstream from the fuel body. These results were obtained under the following inlet conditions: inlet-air temperature was varied from 80° to 220° F, and inlet-air velocity was varied from 117 to 201 feet per second.

A basket was placed at the exit of the combustor to collect unburned fuel blown out during combustion. At an inlet-air velocity of 121 feet per second, 7.2 percent of the fuel charge was collected from the exhaust stream, whereas at an inlet velocity of 201 feet per second, 21.9 percent of the fuel charge was collected from the exhaust stream.

The work on solid fuels at Massachusetts Institute of Technology is being continued with coal. Petroleum coke will also be investigated as a possible fuel.

Jet Propulsion Laboratory,

California Institute of Technology - Carbon

The combustion of carbon in a high-velocity air stream was studied at the California Institute of Technology (reference 4) in order to determine the potentialities of solid-fuel beds for ram-jet application and to substantiate a theoretical analysis by the authors of reference 4 on the kinetics of carbon combustion. The experimental investigation was conducted in a 4-inch-diameter combustor placed inside a furnace, so that the temperature of the carbon could be raised to its ignition temperature. The fuel-bed configurations were made from two sizes of carbon electrodes. Both electrodes were 4 inches in diameter, and one was 6 inches long and the other was 16 inches long. The electrodes were machined into three configurations; namely, hollow cylinders, tubes with seven holes, and tubes with 19 holes. The carbon was burned successfully at inlet air velocities of 100, 200, and 300 feet per second. It was necessary to heat the carbon to 2400° F in order to initiate combustion above an inlet velocity of 125 feet per second. The combustion efficiency obtained in the tests was about 75 percent of theoretical.

The experimental results obtained by the investigators at California Institute of Technology agreed reasonably well with the theory they developed for the burning of carbon tubes. One of their original premises was based on the work of Hottel and coworkers (references 39, 40, and 41) who found that the burning rate of graphite spheres was controlled at low temperatures by chemical resistance to combustion. The reaction rate was doubled for each 59° F rise in the carbon surface temperature. At temperatures between 1340° and 1520° F the rate of combustion was controlled by diffusion of gas to and from the surface of the carbon.

The investigators state that mass transfer is the controlling mechanism in the solid-fuel combustion and hence the heat release rate can be increased by any means that increases the momentum transfer, such as increasing velocity or increasing turbulence level. The later work at Experiment Incorporated and at Continental Aviation on solid fuels seems to confirm the fact that mass transfer is the controlling mechanism.

However, the authors of reference 4 point out that increasing turbulence or gas velocity involves increasing the pressure drop through the combustor. In order to increase heat release rate from a solid-fuel bed at a constant pressure drop, it is necessary to use a fuel of higher heating value or to eject small fuel particles into the air stream. This ejection is probably accomplished by the oxidizer in the burning of solid-fuel formulations.

EXPERIMENTAL COMBUSTION STUDIES - FUEL-FEED SYSTEMS

Bureau of Mines - Coal Pellets and Powder

Pellet feed system. - A burner and feed system were developed at the Bureau of Mines for the burning of fuel pellets in a basket-type combustor. In one arrangement a 6-inch-diameter burner was provided with a basket made in the shape of a truncated cone that was 22 inches long and measured 5 inches in diameter at the upstream end and 3 inches in diameter at the downstream end. The original basket was made of 0.25-inch stainless-steel rods spaced about 0.5 inch apart. Other materials of construction were tried during the course of the work. The fuel pellets were made from coal mixed with a binder and formed into cylinders 1 inch by $1\frac{3}{8}$ inches. The pellets were ignited by use of an incendiary mixture placed upstream from the pellet bed and some of the pellets were coated with the incendiary mixture to carry the reaction through the entire pellet bed. Combustion of the pellets proceeded rapidly and the temperature rise of the gases seemed to indicate satisfactory combustion efficiencies. It was proposed that the fuel burned to carbon monoxide in the fuel bed and then, downstream from the basket, the carbon monoxide burned to carbon dioxide. A hopper-type feed system was developed so that fuel pellets and even stoker coal was fed to the combustor with satisfactory results. The chief problem encountered in this development has been the discovery of suitable materials for construction of the burner basket. A large number of materials has been examined and none has been satisfactory. Apparently at the present time the effort on this project at the Bureau of Mines has been discontinued in favor of other work.

Powder-feed system. - A feed system and burner were developed at the Bureau of Mines for the burning of pulverized coal. The combustor was a 4-inch standard steel pipe, 4 feet long. Several fuel-feed systems were tried. The most successful was operated by maintaining the pulverized coal in a fluidized state with air. The fluidized fuel was forced by air pressure through a $\frac{1}{4}$-inch copper line into the combustion chamber.

Most of the burning tests were conducted in the 4-inch combustor provided with a pilot flame of natural gas and oxygen, with no additional flameholder provided. The air supply system for these tests was the same as that described under the solid fuel work conducted at the Bureau of Mines. In general the burning tests indicated gas temperatures between 2000° and 2400° F.

At the present time the exploratory work at the Bureau of Mines on pulverized fuel has been deferred in favor of more intensive effort on solid metallic fuels.

NACA - Aluminum Powder and Wire

Reference 37 reports an experimental investigation that was conducted to determine the combustion properties of aluminum injected both in powder and wire form into 2-inch-diameter ram-jet type combustors.

Aluminum powder. - The aluminum-powder combustor illustrated in figure 20 was $1\frac{7}{8}$ inches in internal diameter, 30 inches long, and had a nozzle with a $1\frac{1}{4}$-inch exit diameter; the combustor was mounted in a cooling bath. An oscillating flameholder was used to remove solid deposits. Combustion air at room temperature and approximately 1 atmosphere pressure was metered with an A.S.M.E. orifice. Combustion-air velocities ranged from 25 to 55 feet per second. Jet thrust was measured by strain gages that recorded the force on the calibrated thrust target shown in figure 20. The aluminum powder contained in a $1\frac{1}{8}$-inch-diameter injection tube was forced by a piston through a rapidly rotating slotted disk into the combustor. When a cloud of powder and air issued from the combustor, ignition was achieved with a gunpowder squib. For purposes of comparison, a propane system was also installed. The fuel orifices were located approximately 1 foot upstream of the aluminum injector tube. For propane runs, an annular-type flameholder blocking 30 percent of the combustion chamber was used to stabilize the burning.

In 1-minute runs with aluminum powder, smooth combustion was obtained. An optical pyrometer indicated temperatures in excess of 4800° R. Jet thrust was only about 50 percent of the theoretical jet thrust calculated for an ideal air cycle and was 40 percent lower than for propane at comparable values of simulated flight speeds. Excessive solid deposits were formed on the walls of the combustion chamber and exhaust nozzle. The increased internal friction and the reduction in exhaust-nozzle area due to deposits provide the most obvious explanation of the lower thrust of the aluminum burner relative to the propane burner. Combustion efficiencies calculated as percent of theoretical temperature rise by using the outlet temperature determined from the measured jet thrust scattered widely and averaged approximately 50 percent. Similar work has been conducted in a 4-inch-diameter combustor.

<u>Aluminum wire</u>. - For the aluminum-wire combustor, a commercial atomizing metalizing gun was so modified that gas-flow measurements could be made and was affixed to the inlet of a 2-inch stainless-steel standard wall pipe 12 inches long as shown in figure 21 (reference 37). An oxygen-propane flame melted the $\frac{3}{16}$-inch-diameter aluminum wire and a jet of air atomized it into the combustor. Ignition was achieved with a gunpowder squib that was held in the combustor until the walls were coated with an incandescent oxide deposit. The combustor was mounted in a salt-bath that kept the wall temperatures at about 1250° F. The flow and temperatures of gas and water leaving the spray box were recorded to permit a heat balance. Difficulties with ignition, with combustor-wall burn-outs, and with heavy deposits of solid combustion products were experienced. Combustion was stable in the wire combustor at 115 feet per second air velocity even though no flameholder was used. As shown in figure 22, the combustion efficiencies obtained were nearly constant at about 75 percent for fuel-air ratios from 0.08 to 0.20.

<u>Other experiments</u>. - In a few unreported trials, aluminum-impregnated plastic wire was atomized and successfully burned in the aforementioned 2-inch burner.

Royal Aircraft Establishment - Aluminum Powder

The Royal Aircraft Establishment conducted combustion experiments on aluminum flake powder, as used for paint manufacture, in a 6-inch-diameter combustor 21 inches long. The powder was fed to the chamber by an air stream, and was mixed with more air and burned at a swirl-type jet in the back of the combustion chamber (reference 6). The tests reported were at nearly atmospheric pressure; no flow measurements were made. Combustion temperatures of 5400° F were reported.

Rapid deposition of solid oxides on the combustor and exhaust nozzle walls severely limited the test runs. To determine whether sweat cooling would prevent oxide formation on the wall of the exhaust nozzle, tests with a plain water-cooled nozzle were compared with tests in which a porous nozzle with water seeping through it to form a film on the inside wall was used. The porous nozzle eliminated solid deposition with dramatic effectiveness. The quantity of water required to prevent oxide formation in the nozzle was of the same order of magnitude as that calculated to be required for cooling purposes alone.

NACA - Slurry-Fuel Systems

Slurry fuels. - Suspensions, or slurries, of powdered metals in hydrocarbons that have not only high concentrations of metal but also sufficient fluidity to be handled and pumped as liquids have shown excellent promise as ram-jet fuels. Flexibility of flow rate, fuel storage, fuel type, and metal concentration is afforded. The NACA has been investigating the preparation and properties of slurries of aluminum, boron, and magnesium powder in JP-3 fuel (MIL-F-5624). Systematic studies of the properties of the slurries have been made to determine the effect of the metal particle sizes, size distributions, particle shapes, and surface characteristics. The effect on the properties of various slurries of wetting agents that are used to promote fluidity when high metal concentrations are used, and the effect of gelling agents such as aluminum octoate that are used to promote stability have been studied also. The physical properties of the slurries examined have been density, viscosity, stability, and surface tension, and pumping, metering, injection, and spray characteristics.

Figure 23 indicates the effect of metal concentration on density that has been observed. As JP-3 is added to the metal powder, density increases and the mixture becomes pasty; apparently the liquid is wetting the metal surface and filling interstices. At some particular concentration, further addition of liquid decreases density and the mixutre becomes fluid; apparently the liquid is diluting the mixture. The Royal Aircraft Establishment has observed the identical phenomenon (reference 15). The maximum metal concentration and the maximum density that can be reached with a fluid slurry is influenced by particle size and shape. The maximum slurry densities obtained to date in the study are as follows:

Metal in JP-3 (Density of JP-3, 0.75 grams/cc)	Average particle size by weight (microns)	Metal density (grams/cc)	Concentration (percent by weight)	Slurry density (grams/cc)
Aluminum	42	2.7	84	1.8
Boron (amorphous)	21	2.32	64	1.3
Magnesium	66	1.74	83	1.4

The viscosity of metal slurries is a function of the rate of shear, particularly when a gelling agent such as aluminum octoate has been used to provide stability. The viscosity and surface tension of slurry fuels apparently increase very rapidly when a critical concentration of additive is exceeded. For example, the apparent viscosity of a 30-percent superfine (24-micron) magnesium slurry increases from 5.6 centipoises with no additive, to 30 centipoises with 0.5-percent additive, and to 175 centipoises with 1.0-percent additive. Surface tension behaves similarly.

The time for an observed settling of a slurry also is a function of the additive concentration. This phenomenon is indicated by the following data for a 30-percent suspension of superfine magnesium in JP-3.

Additive concentration (percent)	Time for 5 percent settling (hr)	Additive concentration (percent)	Time for 5 percent settling (hr)
0	0.45	0.56	72
.16	.11	.64	190
.32	.19	.80	230
.40	.24	1.00	1500
.48	2.7	1.20	>2000

In the absence of additives, higher concentrations of metal settle more slowly than lower concentrations. Higher concentrations of metal require more additive to make them stable than do lower concentrations. The effect of metal size and shape is quite pronounced. The effect of temperature also is quite pronounced, with higher temperatures promoting more rapid settling.

A screw-type pump with a stainless-steel rotor and a synthetic-rubber (Ameripol) stator has delivered slurries satisfactorily, although wear of the pump stator has been encountered, particularly with aromatic fuels. Metering and flow characteristics of magnesium slurries up to 60-percent concentration were similar to the hydrocarbon carrier. The slurry fuels followed the conventional orifice equation.

Photographs viewed along the axis of a spray bar, with the liquid jets normal to the direction of air flow, indicated that the spray dispersion of slurries containing no gel additives was similar to the clear reference fuel, as shown in figure 24 from reference 14. With increasing concentration of gel additives, a coarsening of the fuel sprays is observed, as seen in figure 25, for a higher air velocity. This phenomenon is not surprising in view of the much higher viscosities accompanying the use of gelling agents. Air-atomization has been used with good effect to produce finer sprays.

Photographs illustrating the flow of slurry fuel behind flameholders revealed that the slurry fuel did not enter the recirculation, piloting zone as readily as did the base hydrocarbon fuel alone (reference 14). Remedies for this have included small scoops attached to the trailing edge of otherwise conventional V-type flameholders and injection of the slurry fuel in the plane of the trailing edge of the flameholder and directly behind the flameholder.

Although initial experimentation has offered much encouragement for the production of fluid slurries of high metal concentration suitable as ram-jet fuels, more work must be done before slurries with predictable and desirable properties are achieved.

Magnesium-slurry combustion. - An experimental investigation was conducted to determine the combustion properties of several magnesium-hydrocarbon slurry blends in a 6-inch-diameter simulated tail-pipe burner (reference 14). A diagrammatic sketch of the apparatus is shown in figure 26. Provision was made for measuring flows, heat rejection, and thrust. Propane was burned in the turbojet combustor shown to provide an inlet-air temperature of 1200° F at a constant combustion-air mass flow of about $2\frac{1}{2}$ pounds per second. Four slurry combustor configurations were examined. The most satisfactory configuration of the four was one with fuel injected from eight 0.050-inch orifices spaced symmetrically in the burner wall at a station $\frac{1}{4}$ inch downstream of a single-span, V-type flameholder that blocked 31 percent of the combustor cross section.

Slurries of atomized magnesium of 5, 13, 30, and 60 percent in JP-3 (MIL-F-5624) were burned. In all but the configuration just described, clogging of fuel lines, or some deposits, or burned flameholders were experienced. With the combustor described, however, results as shown in figure 27 were obtained. The net thrust is defined as the jet thrust of the tail-pipe burner minus the jet thrust of the precombustor (tail-pipe burner off) per pound of combustion air; the air specific impulse is the total stream momentum per pound of combustion air at an exit Mach number of 1. It was necessary to use a different burner configuration to get operation with the base fuel alone at mixture ratios other than those shown in figure 27. The high-concentration magnesium slurries showed large improvements in combustion stability and tail-pipe burner net thrust. The 30- and 60-percent magnesium slurries burned stably between 0 and 1.4 equivalence ratio, limited by pump capacity rather than combustion. Combustor inlet-air velocities were approximately 330 to 440 feet per second. Compared with the base fuel alone, MIL-F-5624, 30- and 60-percent magnesium slurries produced 15 and 51 percent increase in net tail-pipe burner thrust, corresponding to 5 and 14 percent increase in air specific impulse, respectively. The 60-percent magnesium slurry exhibited an impulse efficiency of 94 percent. The high reactivity of the magnesium slurry fuels as indicated by high efficiencies and wide operating limits is considered one of the most significant features of this type of fuel in that it may lead to operation over wider flight conditions, such as very high altitudes, and it may reduce the blocked area now required for flameholding in hydrocarbon-fueled ram jets and tail-pipe burners.

Other slurry combustion. - Brief, unreported experiments have also been conducted in which a 2-inch-diameter burner has been operated with boron and aluminum and mixtures of these metals with magnesium.

Applied Physics Laboratory,

Johns Hopkins University - Diborane

In 1947, the Applied Physics Laboratory of Johns Hopkins University (reference 5) reported combustion tests of diborane in a 2-inch-diameter combustor. Liquid diborane at about -65° C was fed to the combustor from eight fuel spray bars arranged as "spokes" across the burner. A spark anywhere downstream of the injector would ignite the fuel, even at air flow velocities in excess of 800 feet per second. No spontaneous ignition was observed below 150° C in the presence or absence of water, however. Very stable flames formed in the wake of the spoke injector for fuel-air ratios from leaner than 0.02 to 0.17 with no rich or lean blow-outs in evidence. Thrust measurements did not indicate improvements in thrust over the best experimental values obtained with hydrocarbons in other burners. Deposits of boron oxide, boron, and boron-hydrogen compounds were found at the point of injection, and it was surmised that premature cracking to boron may have been responsible for incomplete combustion. Nevertheless, diborane was demonstrated to have unusual ignition characteristics and very wide ranges of flame stability.

NACA - Diborane

An analytical and experimental study of diborane as a ram-jet fuel is given in reference 9. In the combustion experiments, liquid diborane at -67° F was sprayed from a conventional hollow-cone, swirl-type nozzle with a rated spray angle of 60° into a 2-inch-diameter combustor 2 feet long. Two exhaust nozzles were used, one with no exit reduction (1.875-in. I.D.), and one with a throat diameter of 1.25 inches. Thrust was measured by a target.

Operation of the combustor was smooth and stable over a range of fuel-air ratios from 0.0015 to 0.10 and at combustor inlet-air velocities up to 500 feet per second even in the absence of a flameholder, although the fuel nozzle blocked 30 percent of the cross-sectional area. No blow-out limits could be determined at 2-atmosphere pressure; subatmospheric pressures were not possible with the apparatus. The performance criterion used in reference 9 was air specific thrust, defined as the difference between the measured jet thrust and the calculated inlet thrust divided by the air flow. The burner was not always choked at the exit. Air specific thrusts observed were 80 percent of the ideal values calculated for diborane. The experimental air specific thrusts for diborane were approximately equal to the ideal values for octene-1 for corresponding values of the stoichiometric fraction of fuel. A deposit $\frac{1}{8}$ inch thick or less formed on the burner and nozzle walls; these deposits did not interfere with burner operation during runs for as long as 7 minutes.

In other studies, a spatial flame speed for diborane-air mixtures as high as 169.5 feet per second at a fuel-air ratio of 0.063 was observed under conditions where normal hexane gave a spatial flame speed of 3.22 feet per second or less (reference 9). General Electric Co. has observed and reported the high flame speed and wide inflammability of diborane (references 8 and 42). Concentrations of diborane and pentaborane in air or air-nitrogen mixtures as low as about 1 or 2 percent of the boron hydride yield self-sustaining flames, according to reference 42.

The excellent stability and range of operation observed in ram-jet combustors with diborane is, of course, attributed to the wide inflammability limits and to the extremely high spatial flame speeds of diborane-air mixtures.

Ohio State University - Liquid Hydrogen

The Ohio State University Research Foundation, as an Air Force contractor, has experimented with liquid hydrogen as both a ram-jet fuel and as a rocket fuel (references 10 and 11). Although the emphasis in the research has been on the pumping and handling of liquid hydrogen, some exploratory combustion experiments were performed in a $2\frac{7}{8}$-inch-diameter burner of 17-inch nominal length (reference 10). Entrance velocities up to 120 feet per second and combustion pressures of about 15 pounds per square inch were employed. Liquid hydrogen was injected and burned both in open air and in the combustion chamber at various pressures, and with various types of injection nozzle, but with no flameholder. A straight-stream injector gave insufficient mixing of the hydrogen and air for combustion to occur in the chamber. The best type of injector tested incorporated a splash plate fastened in front of the injector orifice that caused the liquid to spray radially into the passing air. Combustion was maintained over a range of fuel-air ratios of 0.008 to 0.033; stoichiometric is 0.029. Observations indicated that combustion was probably approximately complete over the range of operating conditions tried.

CONCLUDING REMARKS

This report on the status of research on high-energy fuels for ram jets has pointed out that there are fuels other than hydrocarbons that offer performance improvements for ram jets that can be obtained in no other way. The range of long-range, ram-jet-powered vehicles varies directly with the heating value of the fuel on a weight basis, density of the fuel having only a second-order effect. Examination of heating values indicates that beryllium, boron hydrides, liquid hydrogen, boron carbide, boron, and acetylene are the principal materials capable of increasing the ultimate range of ram jets beyond that obtainable with conventional hydrocarbon fuels such as gasoline or kerosene.

Certain other fuels are capable of providing greater stream thrust to a given weight flow of air than is possible with hydrocarbon fuels; this capability is primarily due to the fact that the combustion temperature of about 4200° R obtainable with hydrocarbon fuels can be exceeded with other fuels. The chief fuels capable of providing increased thrust from engines of fixed air handling capacity are magnesium, aluminum, boron or boron carbide, and boron hydrides. Because these fuels also have greater heating values on a volume basis than gasoline, they are particularly suited for applications where a small engine and compact fuel storage are desired - for example, short-range ram-jet-powered vehicles. Carbon also has a high volumetric heating value, but cannot exceed the maximum air specific impulse obtainable with gasoline.

Remarkable simplicity apparently can be achieved by burning fuels for short-duration applications as solid-fuel beds, thus entirely eliminating the fuel-feed system.

An examination of the sources of supply of the fuels mentioned eliminates beryllium and its compounds from consideration. Carbon or coal, petroleum hydrocarbons, acetylene, hydrogen, aluminum, and magnesium may be considered available as fuels. There hardly seems to be enough increase in range to be gained from acetylene when carried as a solid to merit the engineering task of developing its use. The appropriate performance gains with the other fuels appear worth seeking. Boron, boron carbide, and boron hydrides appear to offer unique advantages. Boron hydrides particularly offer substantial increases in long range. Boron or boron carbide offers superior performance to hydrocarbons for long range, for high thrust, and for greater fuel-volume specific impulse, although in each of these three categories there are other fuels that surpass them. But costs, since they represent manpower, must be considered as well as availability. The raw material for producing boron is available, but inexpensive boron metal is not available now, and apparently considerable technological improvements in its production will be required if it is to be inexpensive enough to use at all extensively as a fuel. The same is true for boron carbide. Furthermore, boron must be produced in high purity, greater than the present 82 to 88 percent reported by Bureau of Mines, if its high heating value is to be realized. There is no question but that boron hydrides and certain light metal borohydrides, such as aluminum borohydride, offer great promise, but their use can certainly not be seriously considered unless wholly new methods of producing them are developed. Present costs, or even the most favorable cost estimates based on present synthesis methods, are just too unreasonably high. Thus, the fuels other than hydrocarbons that are currently of particular interest both because of some performance criterions and because of availability and cost are aluminum, carbon or coal, liquid hydrogen, and magnesium. Boron, boron carbide, and boron hydrides are of current interest because of performance criterions and potential cost. Of course, new fuels may be discovered.

There are instances where better thermal data are required for really adequate evaluation of fuel performances; the specific heat, vapor pressure, and heat of vaporization of magnesium oxide, particularly, are needed. Also, the extent to which certain metals may react with nitrogen at high temperatures is uncertain.

All of the fuels just named, except boron carbide, have been investigated to some degree in ram-jet combustion research; none has received sufficient research and development to permit service use. Even application to wholly experimental flight tests has proved difficult because there has not been sufficient work done yet to eliminate all of the many problems attendant upon the development of a new field.

Research on the combustion of aluminum, boron, carbon, and magnesium as solid-fuel beds has been undertaken. Most of the effort has been on coal and on magnesium, with the technique used being that of pressing briquettes from the powdered fuel with binders and oxidizers. Two main techniques of combustion have been tried, in one of which combustion is initiated at the trailing edge of a solid grain that extends into the combustion chamber from the ram-jet center body, and in the other of which combustion is initiated at the upstream end of a perforated grain. In neither case have thoroughly adequate results been achieved, although test-stand work has looked promising. Further work is needed to improve the reliability of combustion rates and the structural integrity of the fuel blocks, or grains. In this further work aluminum should receive effort because of the high thrusts and the high volume specific impulse possible. Boron briquettes for short-duration ram jets appear to have performance potentialities comparable to aluminum, but the cost of boron compared to aluminum must be considered. Magnesium can provide thrust equal to or greater than that possible with aluminum and it has a favorably high volume specific impulse, although not so high as aluminum. Magnesium, furthermore, has proved easier to burn than aluminum, carbon, or boron both because of its greater reactivity with air and because of less serious difficulty with oxide deposits. This research effort on magnesium briquettes should continue in order to realize the improved performance and to aid in the early development of a workable, solid-fuel-bed ram jet. Work on carbon is justified to obtain a cheap, simple unit; carbon cannot give thrusts comparable to the metals just discussed, but its high volumetric heating value should permit good values of British thermal unit per size of fuel grain.

Aluminum powder, powdered coal, coal pellets, magnesium powder, aluminum wire, plastic wire impregnated with aluminum, and stick "flares" of magnesium have all been fed to small, experimental ram-jet combustors with varying degrees of success. Feed methods for solids are in a very primitive state of development. In the case of aluminum, considerable difficulties with combustion chamber deposits have been encountered. Before research is continued far on solid-feed combustion systems, means of storing, conveying, and feeding the solid fuels on a ram-jet aircraft should be carefully planned or worked out in a way that will make possible the realization of the potential performance improvements inherent in these solid fuels.

Slurries, or suspensions in hydrocarbons, of metals provide a way of utilizing the high thrust-producing potential of magnesium or aluminum or either the increased range possibilities or the high thrust potential of boron. Encouraging results have been obtained in the attempt to prepare stable yet fluid slurries of high metal concentration. Further work is needed, however. Combustion work with slurries has been concentrated on magnesium. Suspensions of 15-, 30-, and 60-percent magnesium in JP-3 have burned over wider mixture ratios than hydrocarbons, and of course, produce higher thrusts. The ease of combustion of these slurries is a feature that, added to the performance considerations discussed, urges intensive research and development on slurries and combustion of slurries of these metallic fuels.

Boron hydrides have received little combustion research. Diborane burns easily and rapidly and over wide mixture ratios; it apparently requires very little flameholder in a ram jet. There may be some question about its combustion efficiency, as residues in the combustor have been found to contain unburned boron and boron-hydrogen compounds. As noted, boron hydrides are expensive, and combustion research on them should probably wait until better production and availability can be assured, if it ever can.

From thermodynamic indications, liquid hydrogen offers increased flight range of ram-jet vehicles. Research on liquid hydrogen as a rocket fuel, including pump development, has been conducted (Ohio State University; Aerojet Engineering Corporation) and presumably most of this technology will apply to the ram jet. Exploratory ram-jet combustion tests have been conducted by Ohio State University. Because of its high flame speed and low ignition energy, hydrogen should offer no serious combustion problems; it has been shown to be an excellent piloting fuel. In view of its performance potential for both rockets and ram jets, liquid hydrogen should probably receive research effort involving consideration of launching, aircraft structure, and fuel tankage in sufficient detail to determine whether a significant part of the thermodynamic promise of hydrogen can be realized in actual flight.

In addition to combustion, there are a number of practical problems associated with the use of the fuels discussed that must be solved or circumvented before service use can be realized. The field is sufficiently new that some of these problems have received only cursory attention. Storage and handling methods under service conditions must be established. Reliable pumps, valves, and related hardware must be developed where needed. The combustion products of metallic fuels attenuate radio and radar signals and thus interfere with those tracking and guidance systems that must operate directly astern of the vehicles; tracking and guidance from an angle off-course might be the only solution to this problem.

In general, research directed at effective utilization of high-energy fuels is still in a sufficiently early stage that effort should not only continue along most of the present lines of attack, but also along such new lines of attack as appear promising.

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REFERENCES

1. Schwabl, H.: Investigation on the Suitability of Solid Propellants for Ram Jets. Trans. Rep. No. F-TS-1021-RE, Air Materiel Command, Wright Field (Dayton), Dec. 1946.

2. Damon, Glenn H.: Combustion of Solid Fuels for Ram Jets. Bur. Mines,
   Prog. Rep. No. 3, Proj. NAer 00597, Oct. 1 to Dec. 31, 1946;
   Prog. Rep. No. 4, Proj. NAer 00597, Jan. 1 to March 31, 1947;
   Prog. Rep. No. 5, Proj. NAer 00688, April 1 to June 30, 1947;
   Prog. Rep. No. 6, Proj. NAer 00688, July 1 to Sept. 30, 1947;
   Prog. Rep. No. 7, Proj. NAer 00688, Oct. 1 to Dec. 31, 1947;
   Prog. Rep. No. 8, Proj. NAer 00688, Jan. 1 to March 31, 1948;
   Prog. Rep. No. 9, Proj. NAer 00732, April 1 to June 30, 1948;
   Prog. Rep. No. 10, Proj. NAer 00732, July 1 to Sept. 30, 1948;
   Prog. Rep. No. 11, Proj. NAer 00732, Oct. 1 to Dec. 31, 1948;
   Prog. Rep. No. 12, Proj. NAer 00811, Jan. 1 to March 31, 1949.
   Damon, Glenn H., and Herickes, Joseph A.: Combustion of Solid Fuels for Ram Jets. Bur. Mines,
   Prog. Rep. No. 14, Proj. NAer 00811, July 1 to Sept. 30, 1949;
   Prog. Rep. No. 15, Proj. NAer 00864, Oct. 1 to Dec. 31, 1949;
   Prog. Rep. No. 17, Proj. NAer 00864, April 1 to June 30, 1950;
   Prog. Rep. No. 19, Proj. NAer 01045, Oct. 1 to Dec. 31, 1950.

3. Anon.: Meteor. Meteor Rep. No. 55, Interim Prog. Rep. of Meteor Proj., Guided Missiles Prog., M.I.T., June 1950. (NAVORD Contract NOrd 9661.); Meteor Rep. No. 49, March 1950.

4. Bartel, H. R., and Rannie, W. D.: Solid Fuel Combustion as Applied to Ram Jets. Prog. Rep. 3-12, Power Plant Lab. Proj. No. NX527, Jet Prop. Lab., C.I.T., Sept. 27, 1946. (Air Tech. Service Command Contract No. W-33-038-ac-4320, Ordnance Dept. Contract No. W-04-ORD-455.)

5. Anon.: The Inter-Bureau Technical Committee Conference on Guided Missile Propellants. NAVORD Rep. No. 427, Bur. Ord., June 1947, A Study of Combustion of Solid Fuels for Ram Jets by Glenn H. Damon and Bernard Lewis, pp. 17-33; discussion, pp. 33-34; NACA Jet-Engine Fuel Program by M. Gerstein, pp. 67-68; Combustion Tests with Diborane by W. G. Berl, pp. 151-156.

6. Bowling, A. G.: Use of Sweat Cooling to Prevent Build-Up of Oxide in a Combustion Chamber. Tech. Note No. Aero. 1978, S. D. 86, British R.A.E., Nov. 1948.

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7. Schlesinger, H. I., and Burg, Anton B.: Recent Developments in the Chemistry of the Boron Hydrides. Chem. Rev., vol. 31, no. 1, Aug. 1942, pp. 1-75.

8. Hurd, D. T.: Some Combustion Studies on Diborane. Rep. No. 55223, Res. Lab., Gen. Elec. Co., Sept. 22, 1947. (Proj. Hermes (TU1-2000), Ordnance Dept.)

9. Gammon, Benson E., Genco, Russell S., and Gerstein, Melvin: A Preliminary Experimental and Analytical Evaluation of Diborane as a Ram-Jet Fuel. NACA RM E50J04, 1950.

10. Johnston, H. L.: Liquid Hydrogen Propellant for Aircraft and Rockets. Second Summary Rep., Ohio State Univ. Res. Foundation, July 1, 1947; Third Summary Rep., July 1, 1948. (AFP:431965, Proj. MX-588, Contract W33-038-ac-14794 (16243).)

11. Johnston, H. L.: Liquid Hydrogen Thrust Chamber and Pump Development. Second Ann. Summary Rep., Ohio State Univ. Res. Foundation, April 1, 1950. (SPR 33-2, U.S.A.F. Contract W33-038-ac-19382 (19126).)

12. Squiers, John C.: Summary Report on Solid Fuel Ram-Jet Development. Continental Aviation and Eng. Corp. (Detroit), July 30, 1950. (Air Forces Contract W-33-038-ac-13371.)

13. Wolf, Robert L.: Solid Fuels for Ram-Jet Engines. TM 229, Experiment Incorporated, June 30, 1950.

14. Tower, Leonard K., and Branstetter, J. Robert: Combustion Performance Evaluation of Magnesium-Hydrocarbon Slurry Blends in a Simulated Tail-Pipe Burner. NACA RM E51C26, 1951.

15. Mazurkiewicz, A. G.: Some Rheological Properties of Aluminum Suspensions in Kerosene. Chem. Note 1055, British R.A.E., July 1948.

16. Perry, John H.: Chemical Engineers' Handbook. McGraw-Hill Book Co., Inc., 3d ed., 1950.

17. Anon.: Selected Values of Chemical Thermodynamic Properties. Nat. Bur. Standards.

18. Roberson, E. C.: Thrust and Fuel Economy Characteristics of Potential Ram-Jet Fuels. Rep. R-17, British N.G.T.E., July 1947.

19. Myers, T. E., Friedman, J., and Kanarek, I. A.: Comparison and Evaluation of Rocket Motor Propellant Combination. Rep. AL-998, Proj. MX-770, North American Aviation, Inc., Feb. 7, 1950.

20. Wise, P. H., Serijan, K. T., and Goodman, I. A.: Correlation of Physical Properties with Molecular Structure for Dicyclic Hydrocarbons. I - 2-*n*-Alkylbiphenyl, 1,1-Diphenylalkane, α,ω-Diphenylalkane, 1,1-Dicyclohexylalkane, and α,ω-Dicyclohexylalkane Series. NACA TN 2081, 1950.

21. Lamneck, John H., Jr., and Wise, Paul H.: Synthesis and Purification of Alkyldiphenylmethane Hydrocarbons. I - 2-Methyldiphenylmethane, 3-Methyldiphenylmethane, 2-Ethyldiphenylmethane, 4-Ethyldiphenylmethane, and 4-Isopropyldiphenylmethane. NACA TN 2230, 1950.

22. Goodman, Irving A., and Wise, Paul H.: Synthesis and Purification of Some Alkylbiphenyls and Alkylbicyclohexyls. NACA TN 2260, 1951.

23. Goodman, I. A., and Wise, P. H.: Cicyclic Hydrocarbons. II. 2-Alkylbicyclohexyls. Jour. Am. Chem. Soc., vol. 73, no. 2, Feb. 1951, pp. 850-851.

24. Goodman, Irving A., and Wise, Paul H.: Dicyclic Hydrocarbons. I. 2-Alkylbiphenyls. Jour. Am. Chem. Soc., vol. 72, no. 7, July 20, 1950, pp. 3076-3079.

25. Goodman, I. A., and Wise, P. H.: Correlation of Physical Properties with Molecular Structure for Dicyclic Hydrocarbons. II - 2-Alkylbiphenyl, 2-Alkylbicyclohexyl High-Boiling, and 2-Alkylbicyclohexyl Low-Boiling Series. NACA Proposed TN.

26. Gammon, Benson E.: Preliminary Evaluation of the Air and Fuel Specific-Impulse Characteristics of Several Potential Ram-Jet Fuels. I - Octene-1, Aluminum, and Aluminum - Octene-1 Slurries. NACA RM E51C12, 1951.

27. Gammon, Benson E.: Preliminary Evaluation of the Air and Fuel Specific-Impulse Characteristics of Several Potential Ram-Jet Fuels. II - Magnesium, and Magnesium - Octene-1 Slurries. NACA RM E51C23, 1951.

28. Gammon, Benson E.: Preliminary Evaluation of the Air and Fuel Specific-Impulse Characteristics of Several Potential Ram-Jet Fuels. III - Diborane, Pentaborane, Boron, and Boron - Octene-1 Slurries. NACA RM E51D25, 1951.

29. Huff, Vearl N., and Morrell, Virginia E.: General Method for Computation of Equilibrium Composition and Temperature of Chemical Reactions. NACA TN 2113, 1950.

30. Huff, Vearl N., and Gordon, Sanford: Tables of Thermodynamic Functions for Analysis of Aircraft Propulsion Systems. NACA TN 2161, 1950.

31. Rudnick, Philip: Momentum Relations in Propulsive Ducts. Jour. Aero. Sci., vol. 14, no. 9, Sept. 1947, pp. 540-544.

32. DeMille, John B.: Strategic Minerals. McGraw-Hill Book Co., Inc., 1947, pp. 30-48; 78-85; 281-297.

33. Anon.: Chemical Market Prices. Chem. and Eng. News, vol. 29, no. 19, May 7, 1951, pp. 1900, 1902; June 18, 1951, vol. 28, no. 25, p. 2526.

34. Staffs of the Bureau of Mines and Geological Survey: Mineral Resources of the United States. Public Affairs Press (Washington, D. C.), 1948.

35. Anon.: Minerals Yearbook 1947. U. S. Dept. of Interior.

36. Anon.: Boron Steels Go Into Production. Materials and Methods, vol. 33, no. 4, April 1951, pp. 7, 9.

37. Branstetter, J. Robert, Lord, Albert M., and Gerstein, Melvin: Combustion Properties of Aluminum as Ram-Jet Fuel. NACA RM E51B02, 1951.

38. Anon.: Meteor. Meteor Rep. No. 55, Interim Prog. Rep. of Meteor Proj., Guided Missiles Prog., M.I.T., June 1950. (NAVORD contract NOrd 9661.)

39. Tu, C. M., Davis, H., and Hottel, H. C.: Combustion Rate of Carbon. Ind. and Eng. Chem., vol. 26, no. 7, July 1934, pp. 749-757.

40. Davis, H., and Hottel, H. C.: Combustion Rate of Carbon. Ind. and Eng. Chem., vol. 26, no. 8, Aug. 1934, pp. 889-892.

41. Parker, Almon S., and Hottel, H. C.: Combustion Rate of Carbon. Ind. and Eng. Chem., vol. 28, no. 11, Nov. 1936, pp. 1334-1341.

42. Price, Fraser P.: Flammability Limits of Boron Hydrides. Rep. No. 49A0513, Aero. and Ordnance Systems Div., Gen. Elec. Co., April 1949. (Proj. Hermes (TU1-2000), Ordnance Dept.)

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TABLE I - RESEARCH AND DEVELOPMENT ON HIGH-ENERGY FUELS FOR RAM JETS

[Numbers in parentheses refer to references.]

	Solid-fuel beds				
	Aluminum	Boron	Carbon	Coal base	Magnesium
Bureau of Mines (Active)	Pressed cylinders, boron mixed 6-in. diam.[1] (2)	Pressed cylinders 6-in. diam. (2)	Basic study (2)	Pressed cylinders 6-in. diam. 10-in. diam. (2)	Pressed powder 3.5 in. diam. (2)
Bureau of Standards (Inactive)				Pressed cylinders 6-in. diam. (2)	
CIT-JPL (Inactive)			Electrode graphite cylinders 4-in. diam. (4)		
Continental Aviation (Active)	Pressed cylinders 2-in. diam. (12)	Pressed cylinders 2-in. diam. (12)			Pressed cylinders 6-in. diam. (12)
Experiment, Inc. (Active)	Pressed cylinders 2-in. diam. 6-in. diam. (13)				Pressed cylinders 2-in. diam. 6-in. diam. (13)
General Electric (Active)					
JHU-APL (Inactive)					
MIT (Active)			Basic study (3, 38, 39, 40, 41)	Pressed cylinders and slabs 2 1/4 x 3 in. (3)	
NACA (Active)	Preflight tests of Bureau of Mines fuel	Preflight tests of Bureau of Mines fuel			Preflight tests of Continental fuel
North American Aviation (Active)					(5)
Ohio State University (Active)					
RAE (Inactive)					

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[1] Indicates combustor size.

TABLE I - RESEARCH AND DEVELOPMENT ON HIGH-ENERGY FUELS FOR RAM JETS - Concluded.

[Numbers in parentheses refer to references.]

Fuel-feed systems							
Solid			Liquid				
Aluminum	Coal	Magnesium	Aluminum slurry	Boron slurry	Boron hydrides	Liquid hydrogen	Magnesium slurry
	Powder 2-in. diam. Pellets 4-in. diam. (2)						
		"Flare" injection 2-in. diam. (13)					
					Preliminary combustion (8)		
					2-in. diam. (5)		
Wire 2-in. diam. Powder 2-in. diam. Powder 4-in. diam. (5, 6, 37)			2-in. diam.	2-in. diam.	2-in. diam. (9)		2-in. diam. 6-in. diam. (14)
						2 7/8 in. diam. (10)	
Powder 6-in. diam. (6)			Slurry prepared; no burner tests (15)				

TABLE II - HEATING VALUES OF HIGH-ENERGY FUELS

[Values from reference 16 except as noted.]

Fuel	Melting point (°F)	Boiling point (°F)	Specific gravity	Stoichiometric fuel-air ratio	Oxides[a]	Heat of combustion		
						(Btu/lb)	(Btu/cu ft)	(Btu/lb air)
Acetylene	-115.2	-118.5	0.621 (-119° F)	0.0755	$CO_2;H_2O$	20,740	804,000	1567
Aluminum	1220	3735	2.70	.261	Al_2O_3	13,320	2,246,000	3475
Beryllium	2336	5013	1.816	.131	BeO	26,950	3,055,000	3525
Boron (amorphous)	4172	4622	2.32	.105	B_2O_3	23,280	3,372,000	2436
Boron carbide (B_4C)	4442	> 6332	2.54	.100	$B_2O_3;CO_2$	25,200[b]	3,996,000[b]	2526[b]
Carbon (graphite)	> 6332	7592	2.26	.0871	CO_2	14,110	1,991,000	1229
Diborane	-265.9	-134.5	0.447 (-134.5° F)	.0669	$B_2O_3;H_2O$	31,470	878,800	2108
1-Ethylnaphthalene	5	486	1.008	.0755	$CO_2;H_2O$	17,020	1,074,800	1289
Gasoline	< -76	100-340	0.73	.0678	$CO_2;H_2O$	18,800	856,700	1275
Hydrogen	-434.6	-422.9	0.0709 (-423° F)	.0292	H_2O	51,660	228,600	1510
Lithium	366.8	2502	0.53	.201	Li_2O	18,450	610,500	3714
Lithium hydride	1256	-------	0.82	.115	$Li_2O;H_2O$	17,750[c]	908,400[c]	2046[c]
Magnesium	1202	2025	1.74	.353	MgO	10,810	1,174,000	3813
Pentaborane	-52.4	136.4	.61	.0763	$B_2O_3;H_2O$	28,820	1,098,000	2200
Silicon	2588	4712	2.4	.203	SiO_2	13,176	1,974,000	2681
Silane (SiH_4)	-301	-170	0.68 (-301° F)	.116	SiO_2,H_2O	18,000	764,000	2094
Titanium	3272	> 5432	4.50	.347	TiO_2	8,192	2,301,000	2845

[a] Condensed phases at approximate room temperature, except $H_2O(g)$.

[b] Reference 17.

[c] Calculated from heats of formation in reference 18.

TABLE III - CARBONACEOUS FUEL COMPOSITIONS INVESTIGATED BY THE BUREAU OF MINES

Ingredient	A	B	C	D	E	F	G	H
Coal	80	60	40	40	45	65	55	50
Aluminum		20	40	35	20			
Magnesium						15	15	30
Boron					5			
Sodium nitrate				5	10			5
Sulfur							10	
Nitrocellulose binder	20	20	20	20	20	20	20	15
Specific density	1.27	1.35	1.40	1.45	1.45	1.37	1.32	1.30
Heating value (Btu/lb)	13,550	13,150	12,800	12,050	12,000	13,000	11,950	11,850

TABLE IV - METALLIC FUEL COMPOSITIONS INVESTIGATED BY THE BUREAU OF MINES

Ingredient	MFM-1	MFM-18	MFM-20	MFM-25	MFM-31	MFM-35	MFM-41	MFM-47	MFM-49	MFM-50
Aluminum (pyrotechnic grade)	45	65	45	45	55	-----	-----	25	25	65
Magnesium	-----	-----	-----	-----	-----	-----	65	30	30	-----
Boron	-----	-----	20	-----	10	65	-----	10	10	-----
Sulfur	-----	-----	-----	20	-----	-----	-----	-----	5	10
Silicon	15	-----	-----	-----	-----	-----	-----	-----	-----	-----
Potassium nitrate	25	25	25	25	25	25	25	25	21.4	17.9
Copper sulfate	15	10	10	10	10	10	10	10	8.6	7.1
Oxygen coefficient[1]	0.200	0.189	0.129	0.182	0.153	0.075	0.254	0.170	0.135	0.115
Density	1.50	1.52	1.33	1.50	1.42	1.04	1.26	1.25	1.25	1.41
Calculated heat of combustion (Btu/lb)	7450	8200	10200	6350	9200	14750	6500	8450	8700	8750
Calculated heat of combustion (Btu/cu ft $\times 10^{-3}$)	695	778	850	591	817	951	514	659	678	770
Burning rate in iron case (in./sec)	0.43	0.47	1.11	0.43	0.89	1.89	1.12	-----	-----	-----
Burning rate in magnesium case (in./sec)	-----	0.53	1.5	0.44	1.1	-----	1.17	1.36	1.33	0.61

[1] Ratio of oxygen supplied by oxidants to total amount of oxygen required for complete oxidation of fuel.

TABLE V - RESULTS OF EVALUATION OF ANNULAR FUEL CHARGE IN PREFLIGHT FACILITY AT WALLOPS ISLAND

Mach number	L^*	Oxidizer (percent)	Air temperature T_{So} (^oR)	Air (lb/sec)	Fuel weight (lb)	Burning time (sec)	Average specific impulse ((lb)(sec)/lb air)
2.2	51.3	5	707	13	7.92	3.94	120
2.2	51.3	7.5	694	13	7.98	2.96	130
2.2	43	10	700	13	7.92	2.5	140
2.2	43	12.5	711	13	8.11	3.74	116
2.2	41	7.5	709	13	14.68	5.5	124
2.2	40	5	702	13	14.62	4.85	113
1.6	41	7.5	684	9	14.62	7.75	123
1.6	43	7.5	679	9	7.6	6.1	116

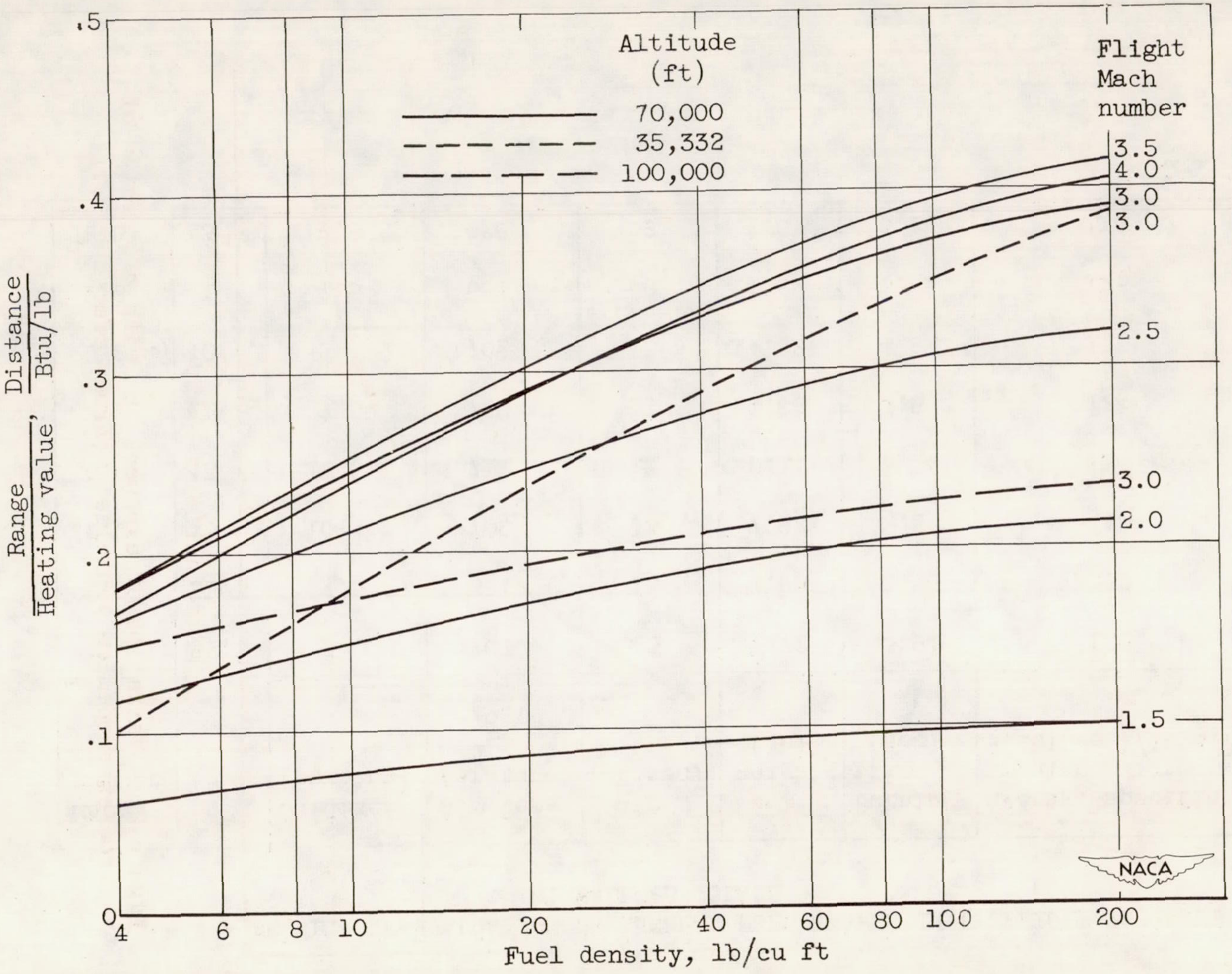

Figure 1. - Effect of fuel heating value and density on range of ram-jet aircraft. Gross weight, 150,000 pounds; pay load, 10,000 pounds.

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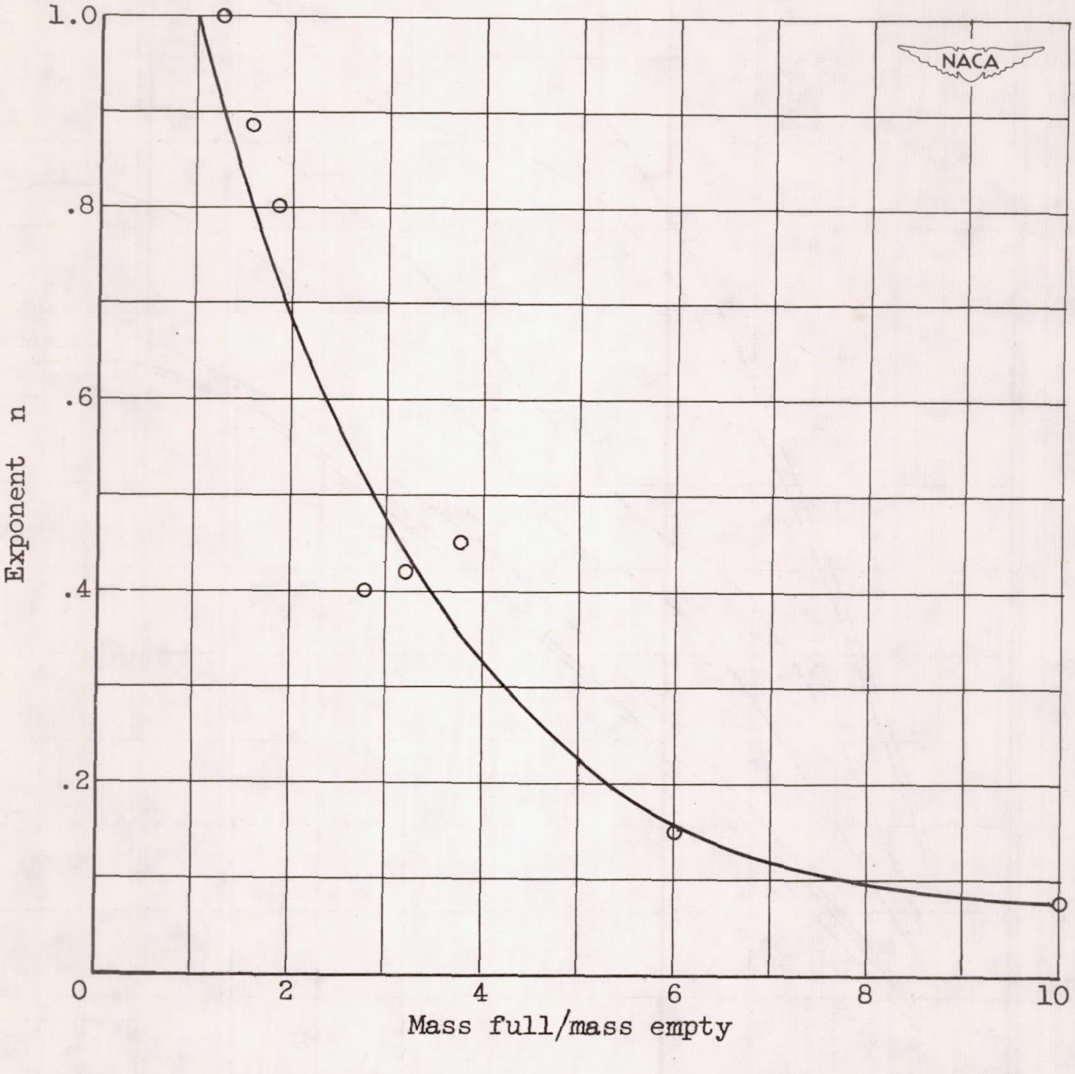

Figure 2. - Variation of exponent n with mass ratio of rocket-propelled vehicles. (From reference 19.)

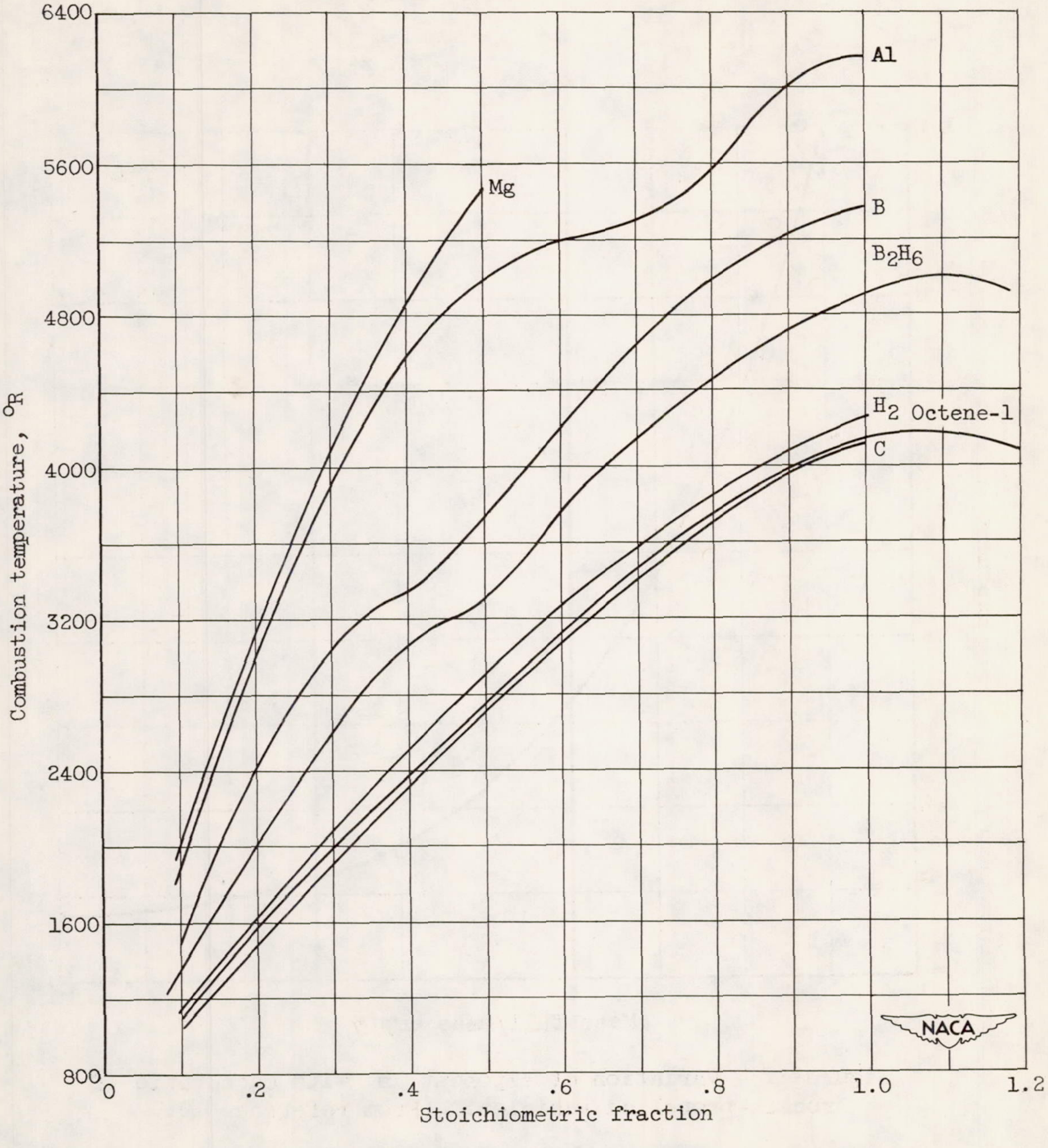

Figure 3. - Theoretical combustion temperatures of several fuels. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres. (From references 26, 27, and 28.)

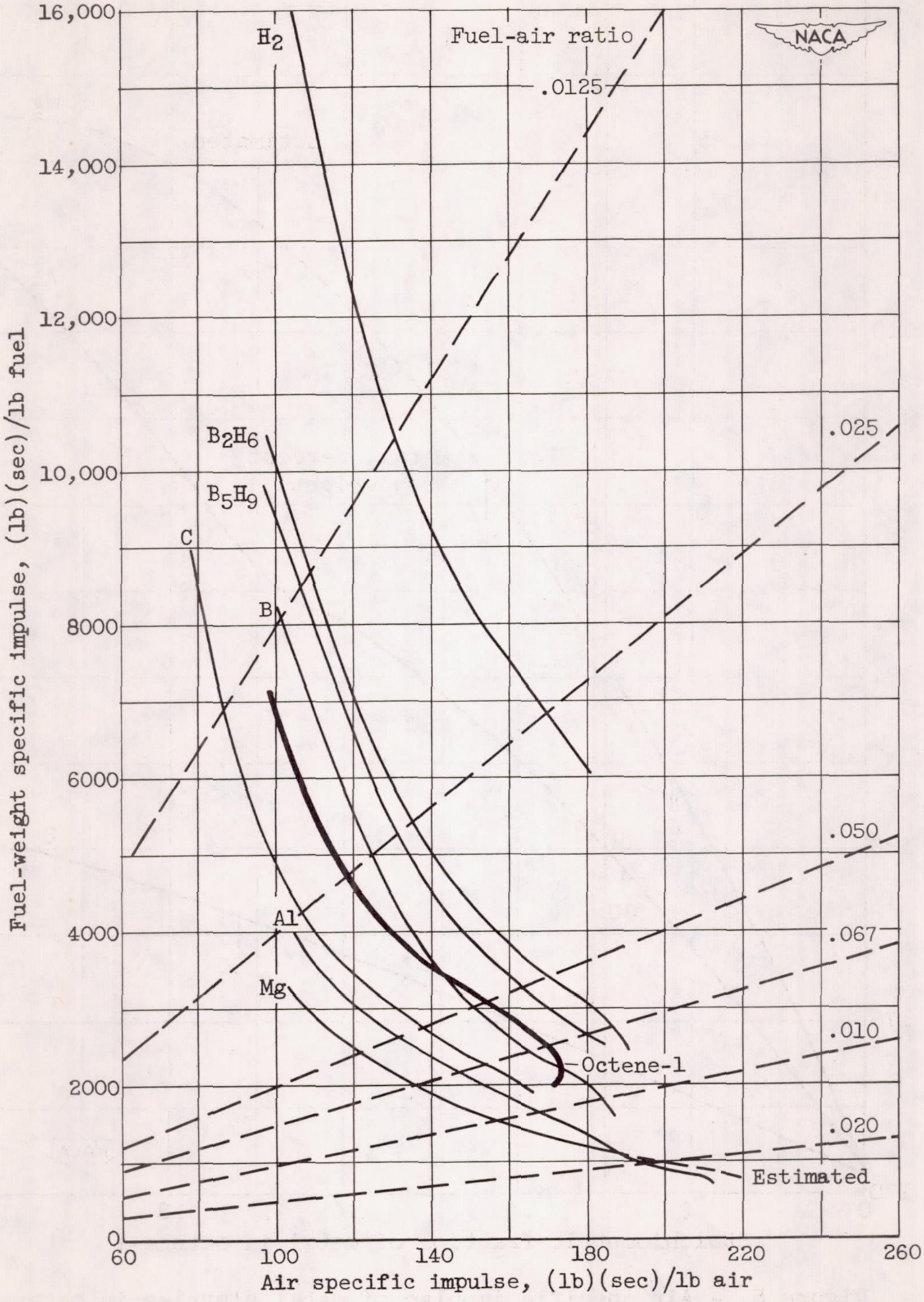

Figure 4. - Variation of fuel-weight specific impulse with air specific impulse for several ram-jet fuels. Combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres. (From references 26, 27, and 28.)

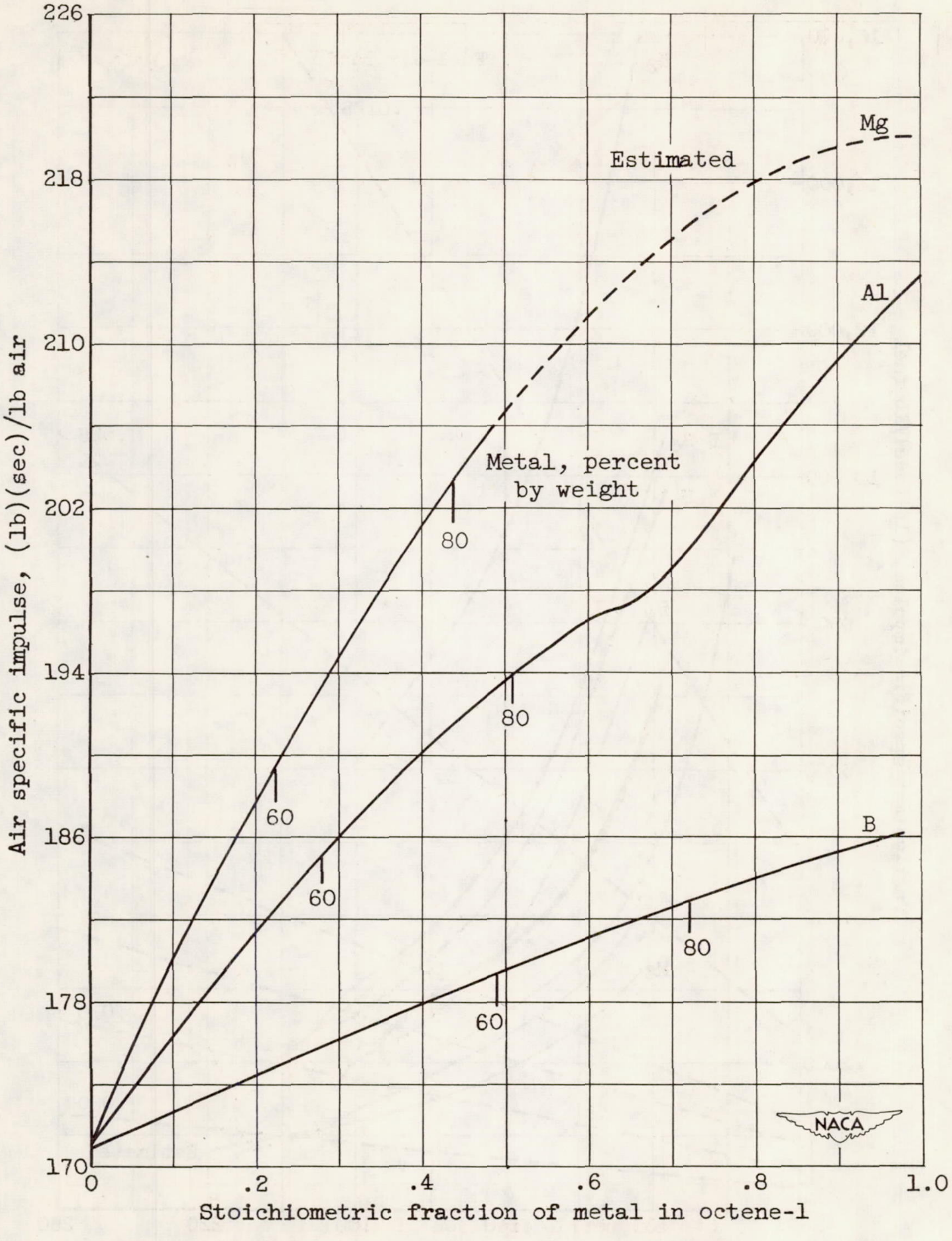

Figure 5. - Air specific impulse of metal slurries in octene-1. Stoichiometric fraction of slurry fixed at 1.0; combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres. (From references 26, 27, and 28.)

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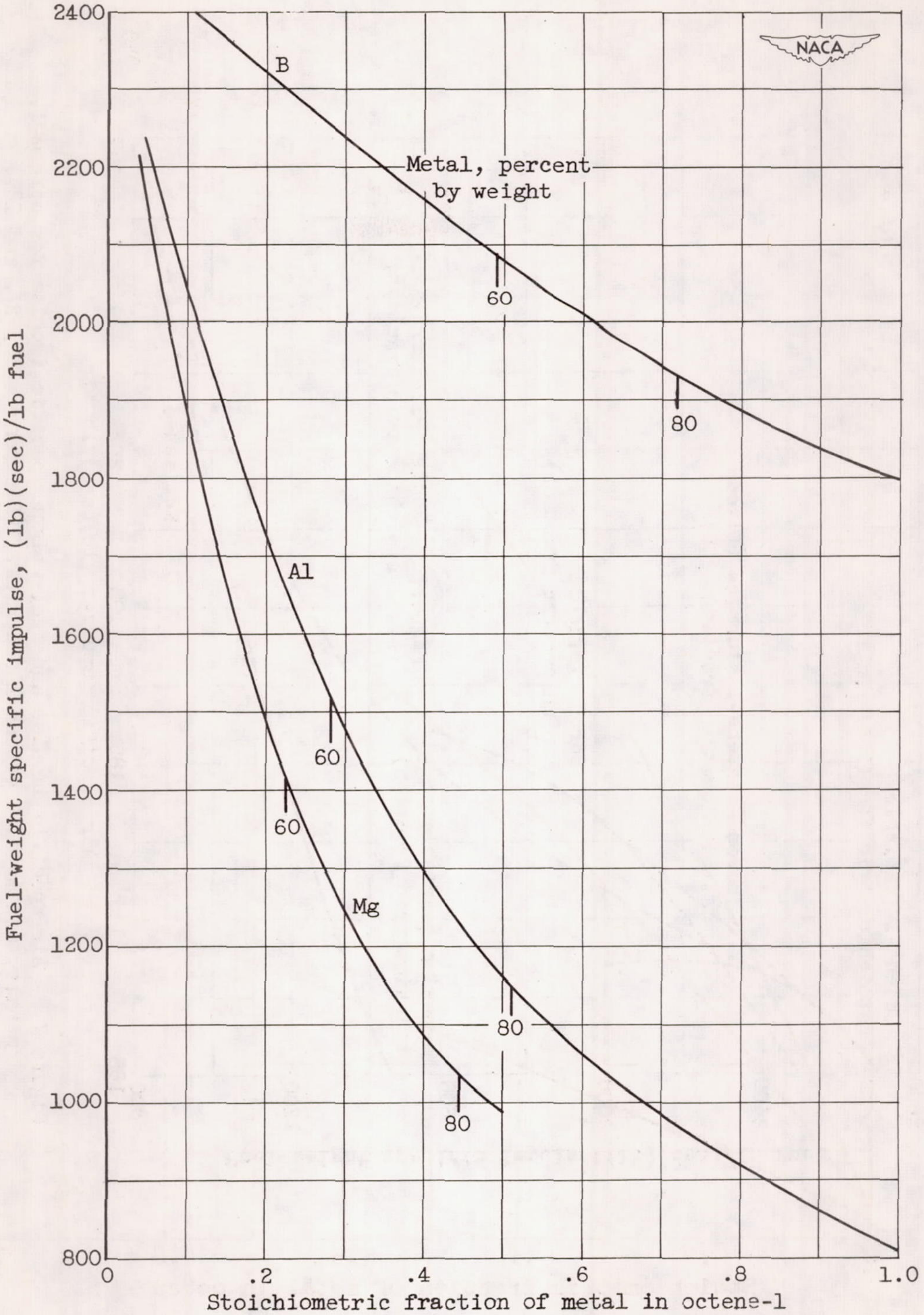


Figure 6. - Fuel-weight specific impulse of metal slurries in octene-1. Stoichiometric fraction fixed at 1.0; combustor inlet-air temperature, 560° R; inlet-air pressure, 2 atmospheres. (From references 26, 27, and 28.)

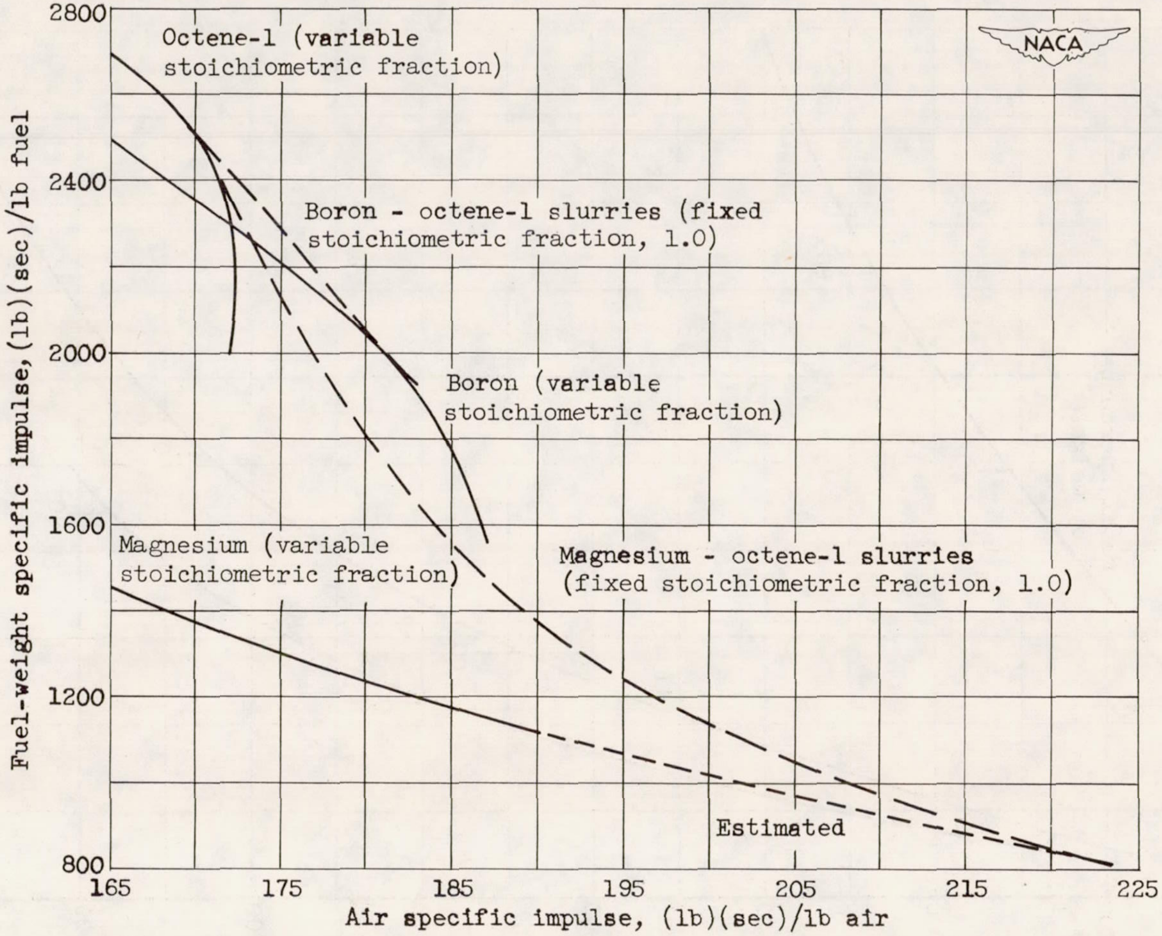
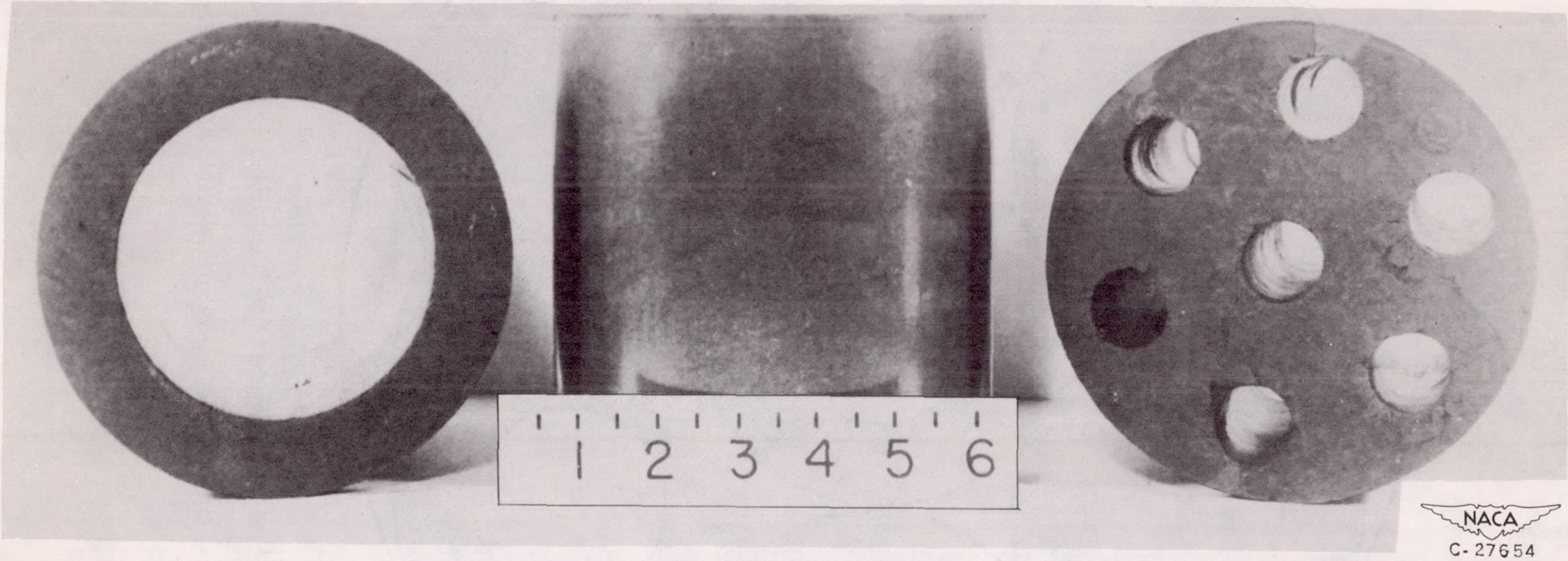


Figure 7. - Air specific impulse and fuel-weight specific impulse for octene-1, metals, and metal - octene-1 slurries. (References 26, 27, and 28.)



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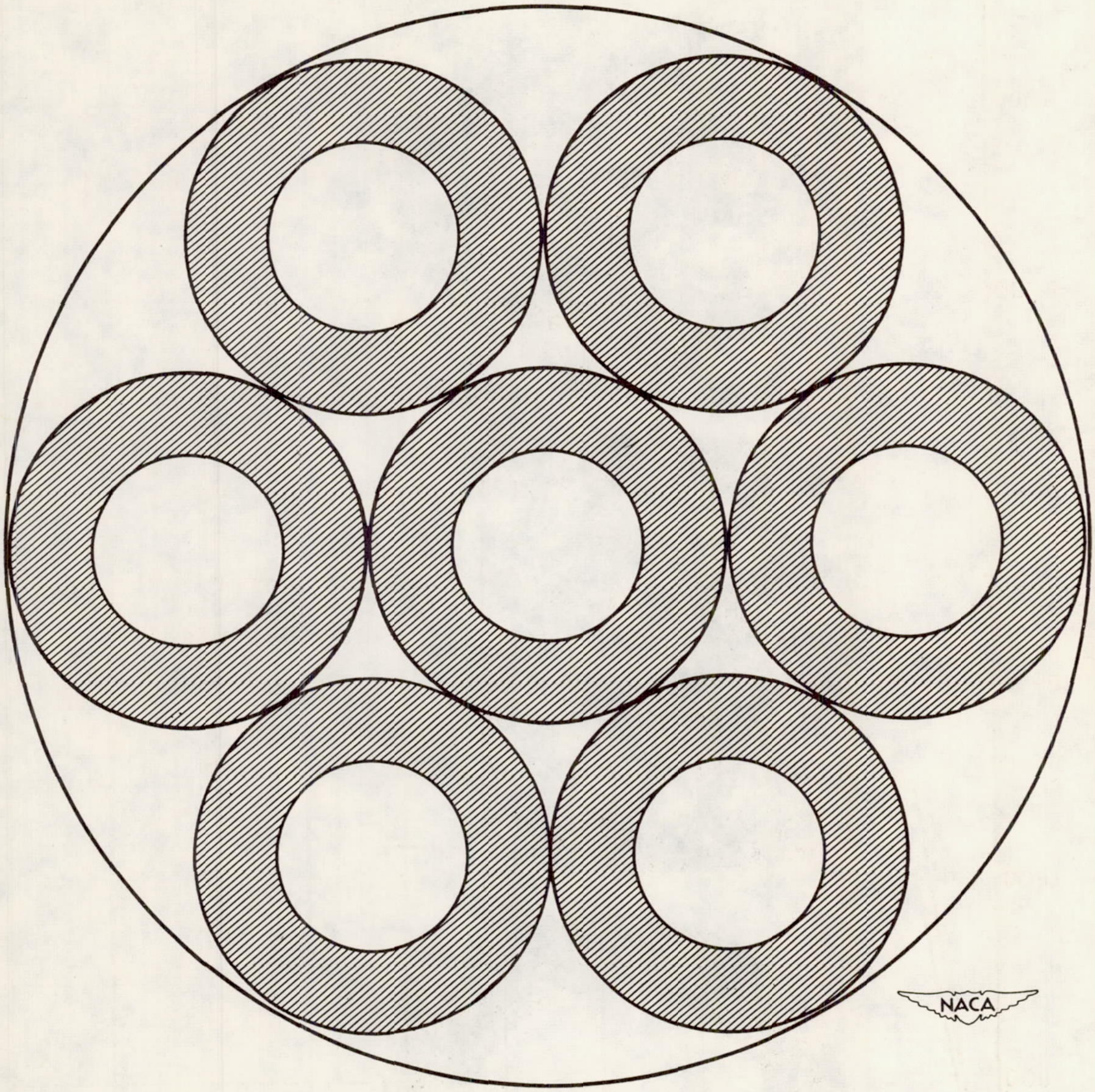
(a) Briquette configuration for 6-inch combustor.

Figure 8. - Carbonaceous fuel charges.



(b) Briquette configuration for 10-inch combustor.

Figure 8. - Concluded. Carbonaceous fuel charges.

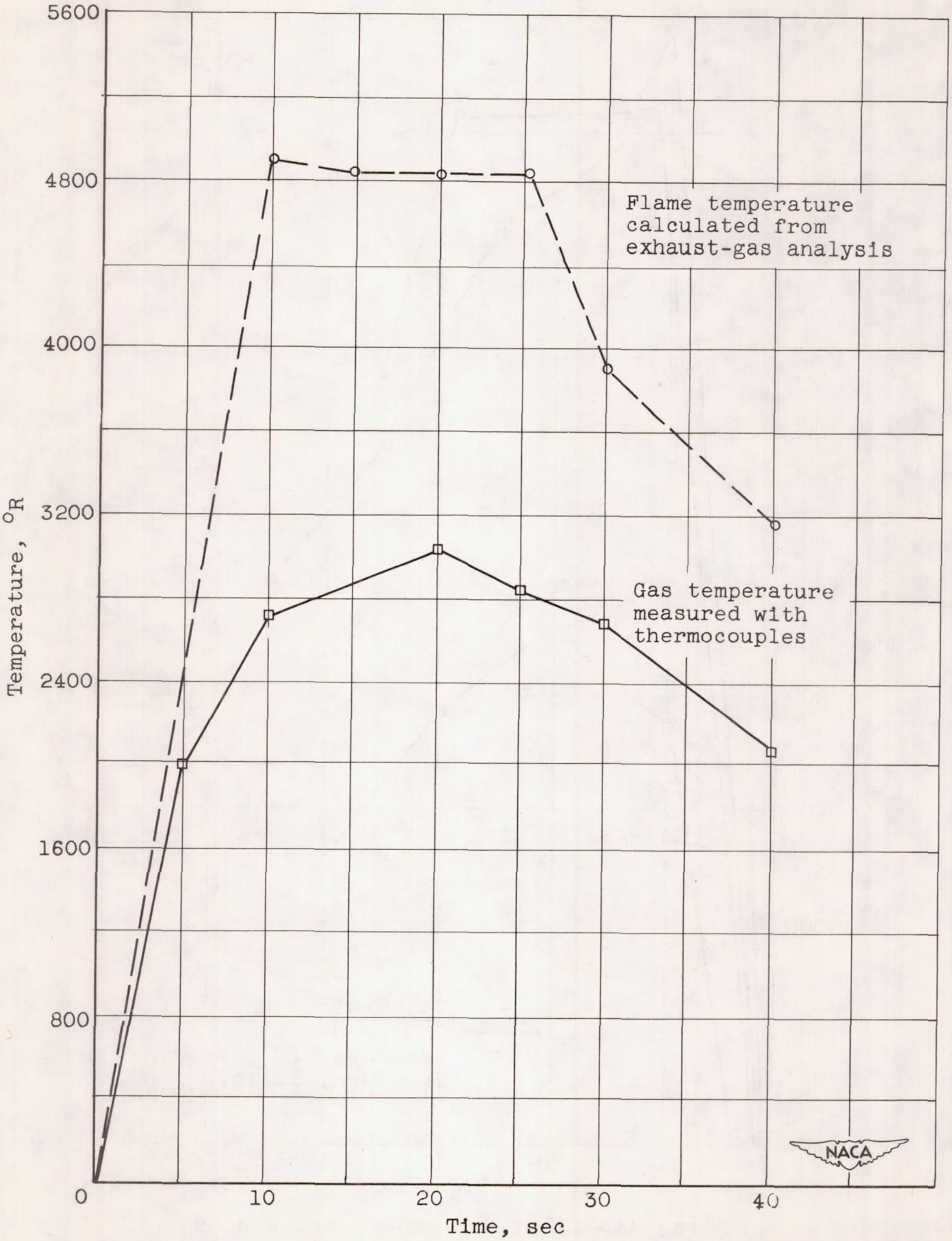
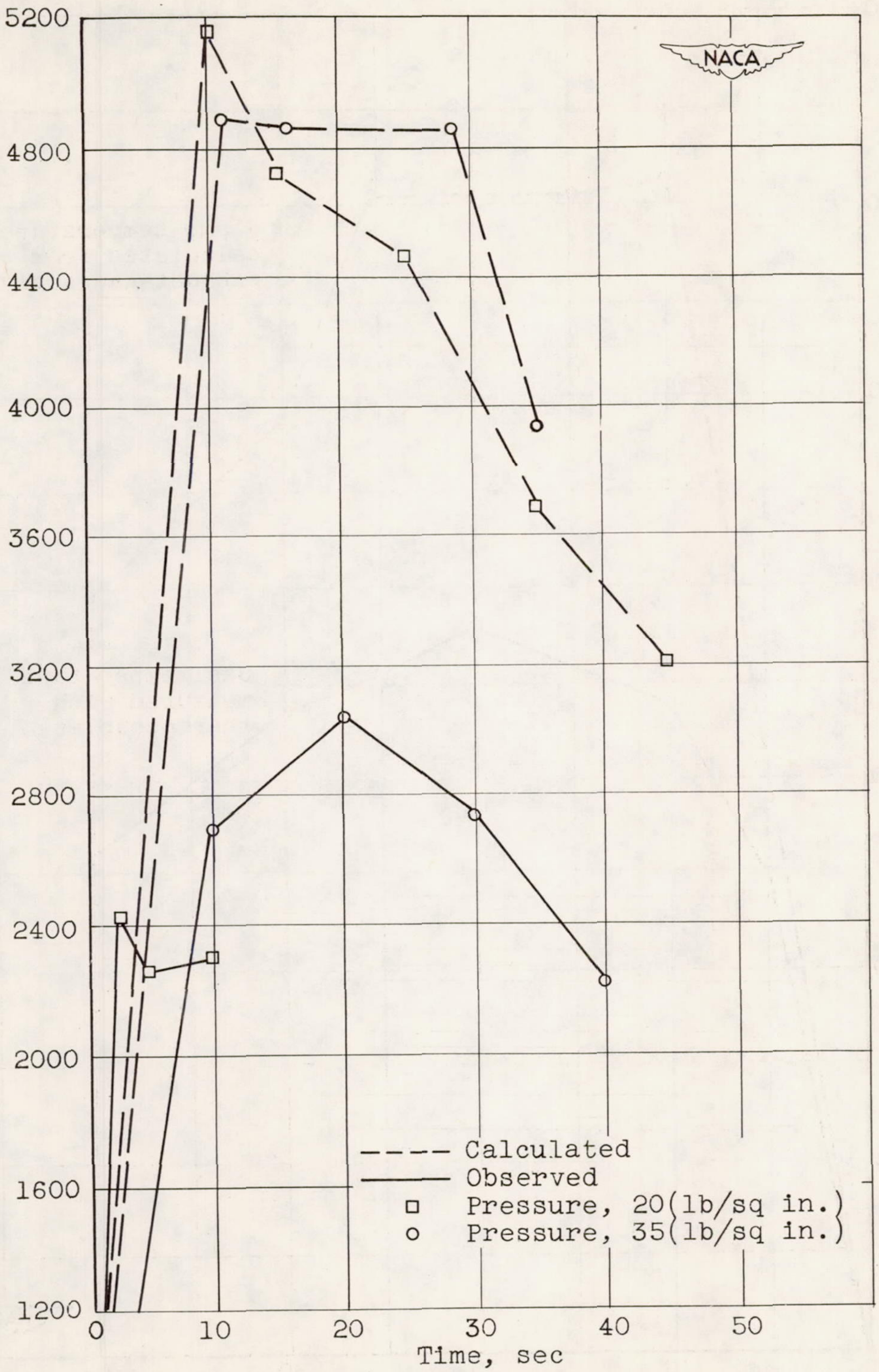
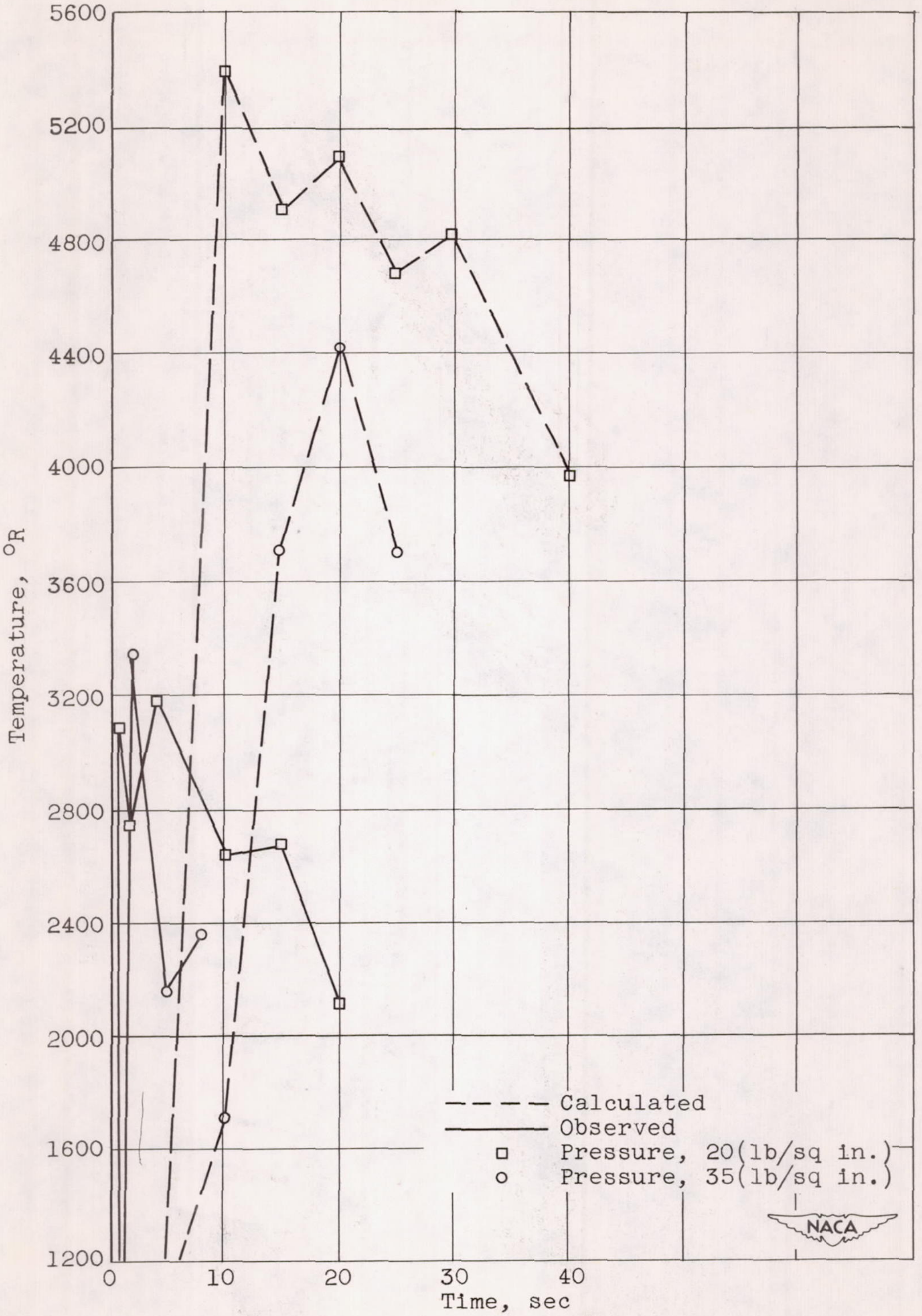


Figure 9. - Temperatures attained with carbonaceous fuel "H". (Table III.)



(a) ~~Air-flow~~, 2.4 pounds per second.

Figure 10. - Temperature-time curves attained with carbonaceous fuels at Bureau of Mines.



(b) Air flow, 3.0 pounds per second.

Figure 10. - Concluded. Temperature-time curves attained with carbonaceous fuels at Bureau of Mines.

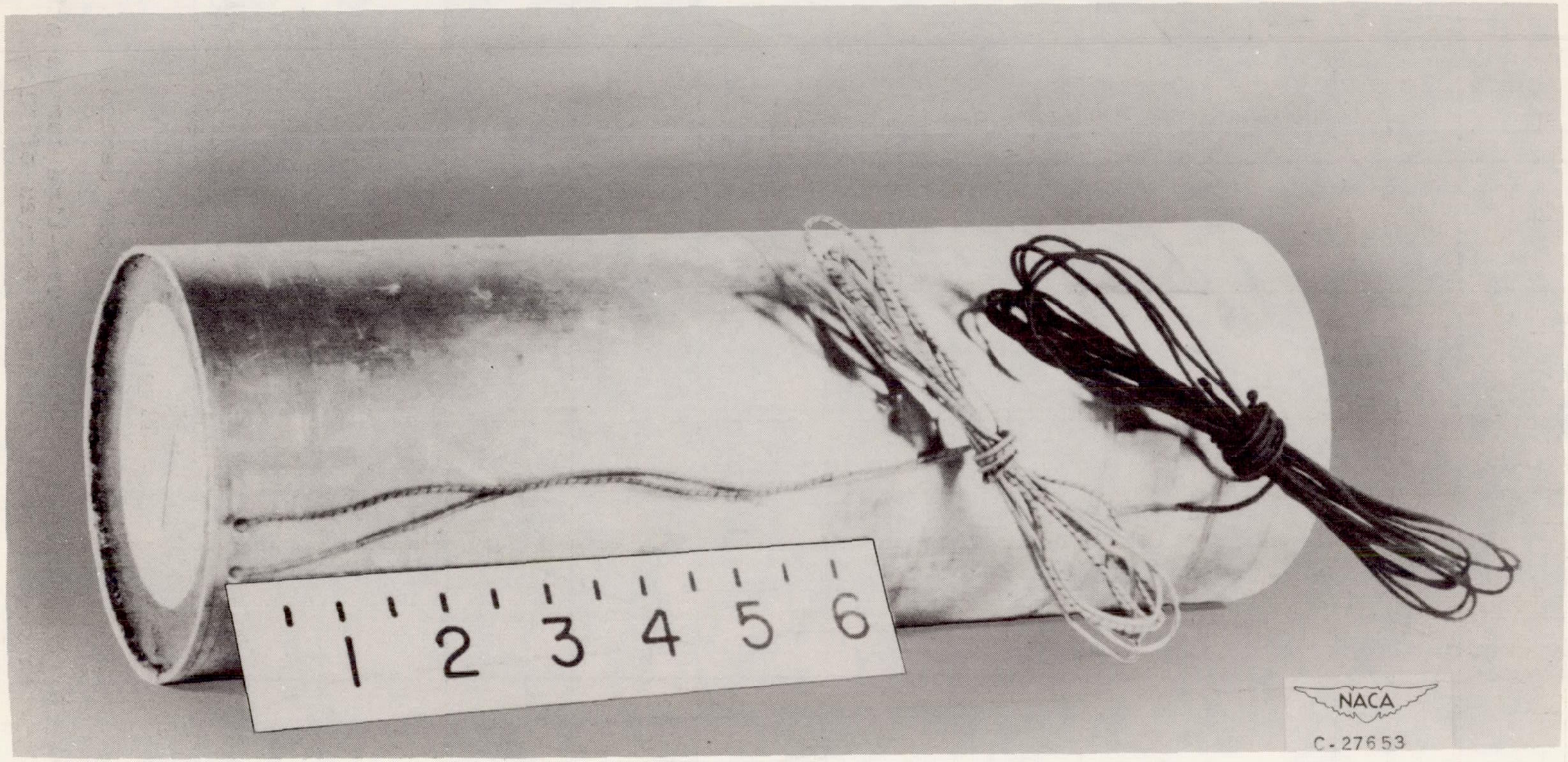


Figure 11. - Metallic fuel charge.

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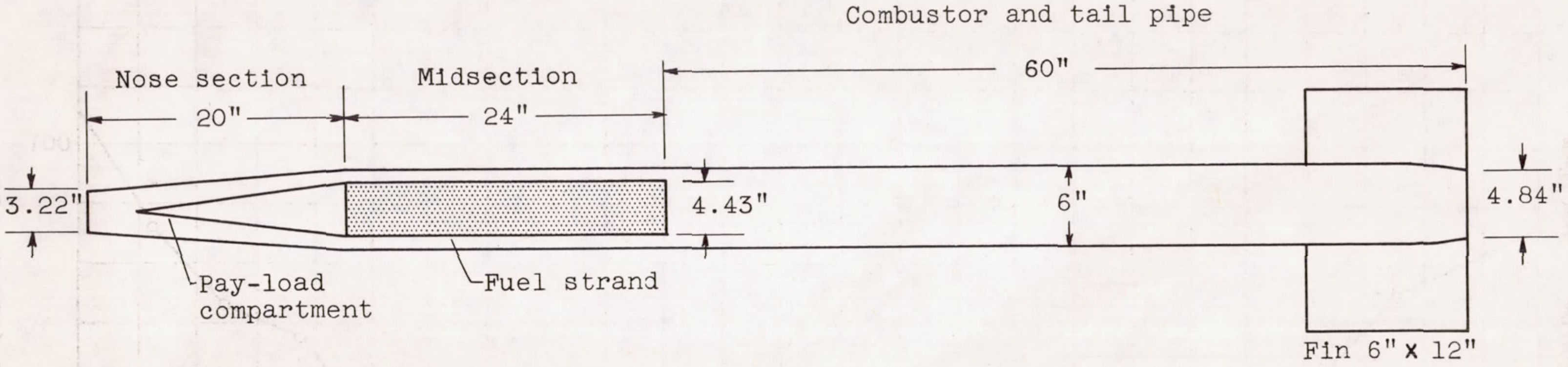

Figure 12. - Application of cigarette burning solid fuel to ram jet.

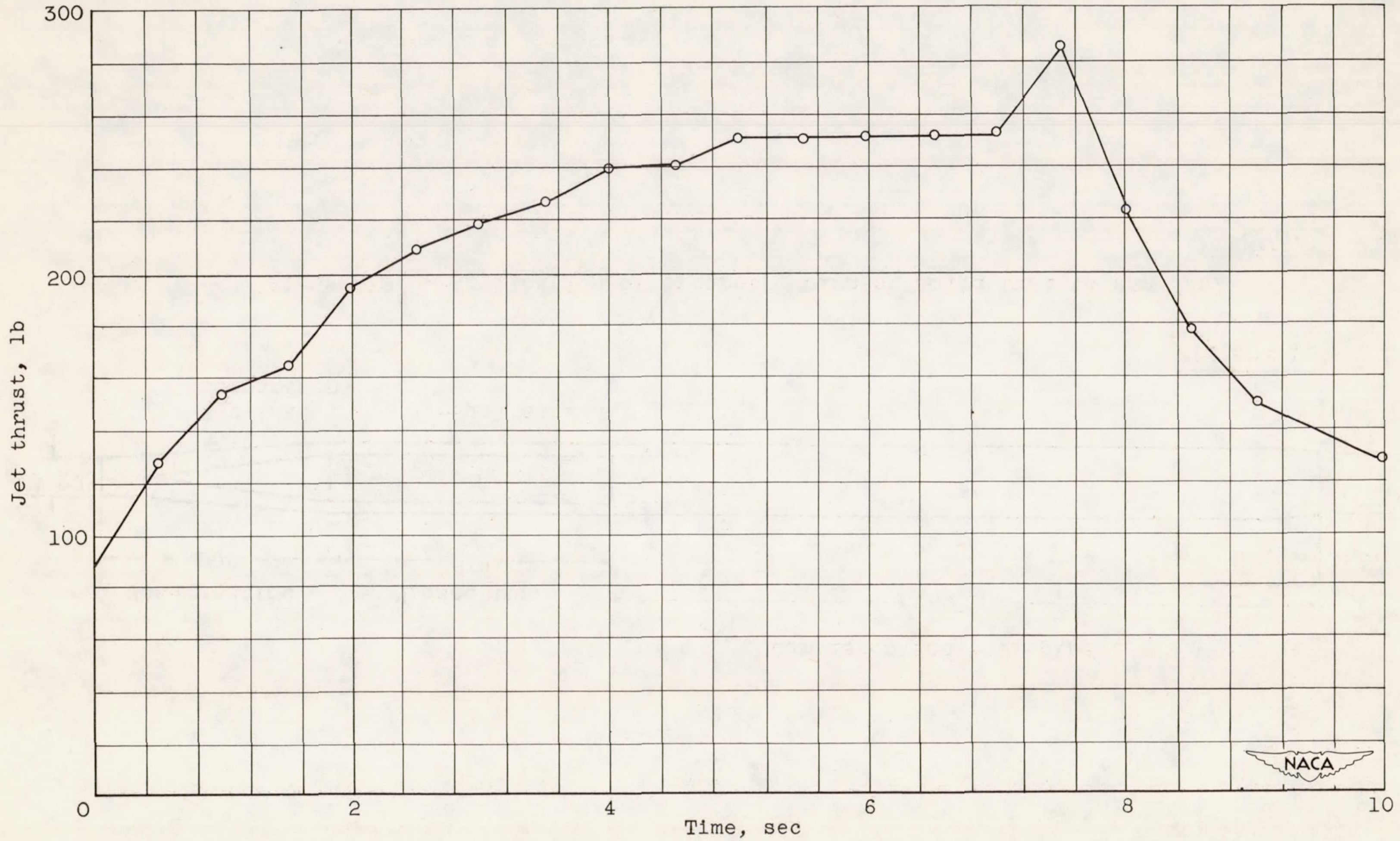

Figure 13. - Thrust curve for metallic fuel MFM-31 from Bureau of Mines. Air flow, 5 pounds per second; fuel flow, 0.7 pound per second; simulated flight Mach number, 1.05.

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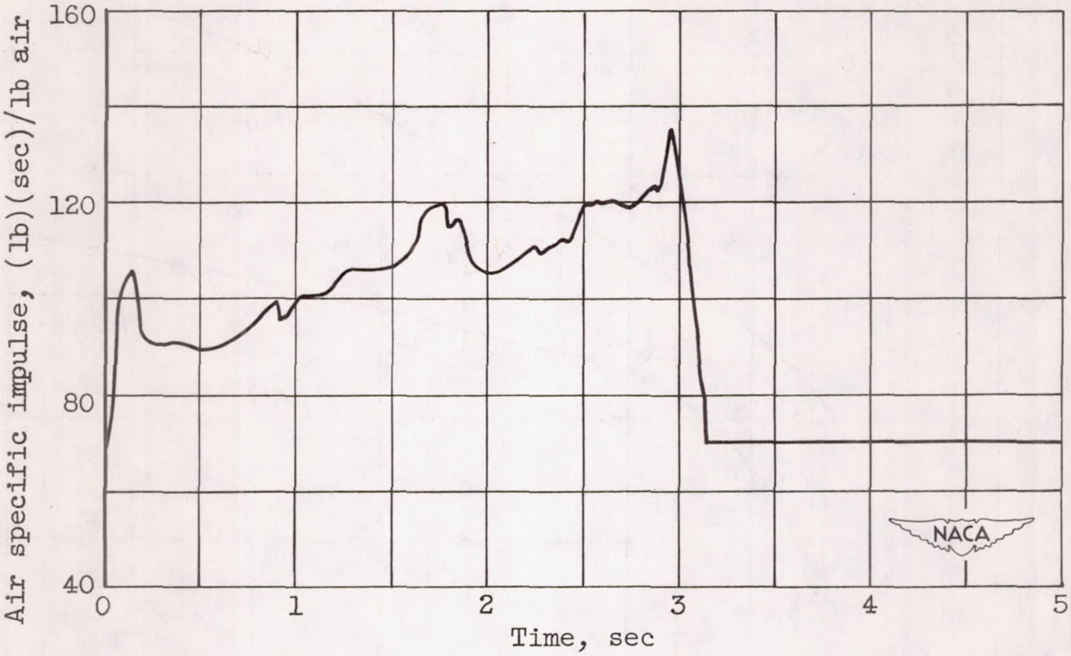

Figure 14. - Air specific impulse obtained with cigarette-type fuel charge evaluated on preflight facility at NACA, Wallops Island. Fuel, MFM-20; inlet-air temperature, 769° R; simulated flight Mach number, 2.2; combustor length, 48 inches; average specific impulse, 107; air flow, 12.5 pounds per second; total fuel weight, 6.24 pounds.

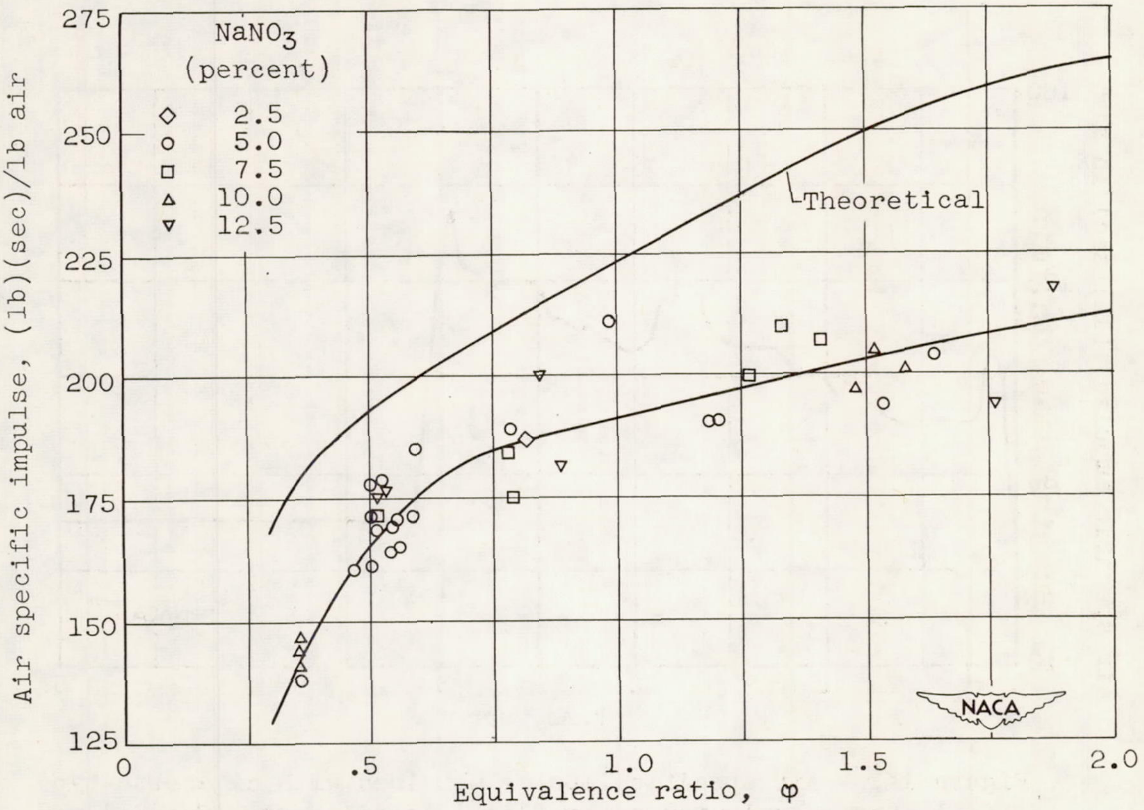

Figure 15. - Variation of air specific impulse with equivalence ratio for magnesium fuel in a 6-inch burner. Air flow, 4.1 to 5.4 pounds per second; air temperature, 605° to 581° R; pressure, 24.4 to 36.2 pounds per square inch gage; fuel, 2 percent boiled linseed oil + M_g + $NaNO_3$; charge, 6 inches O.D. × 4 inches I.D.; L*, 62 inches. (Reference 12.)

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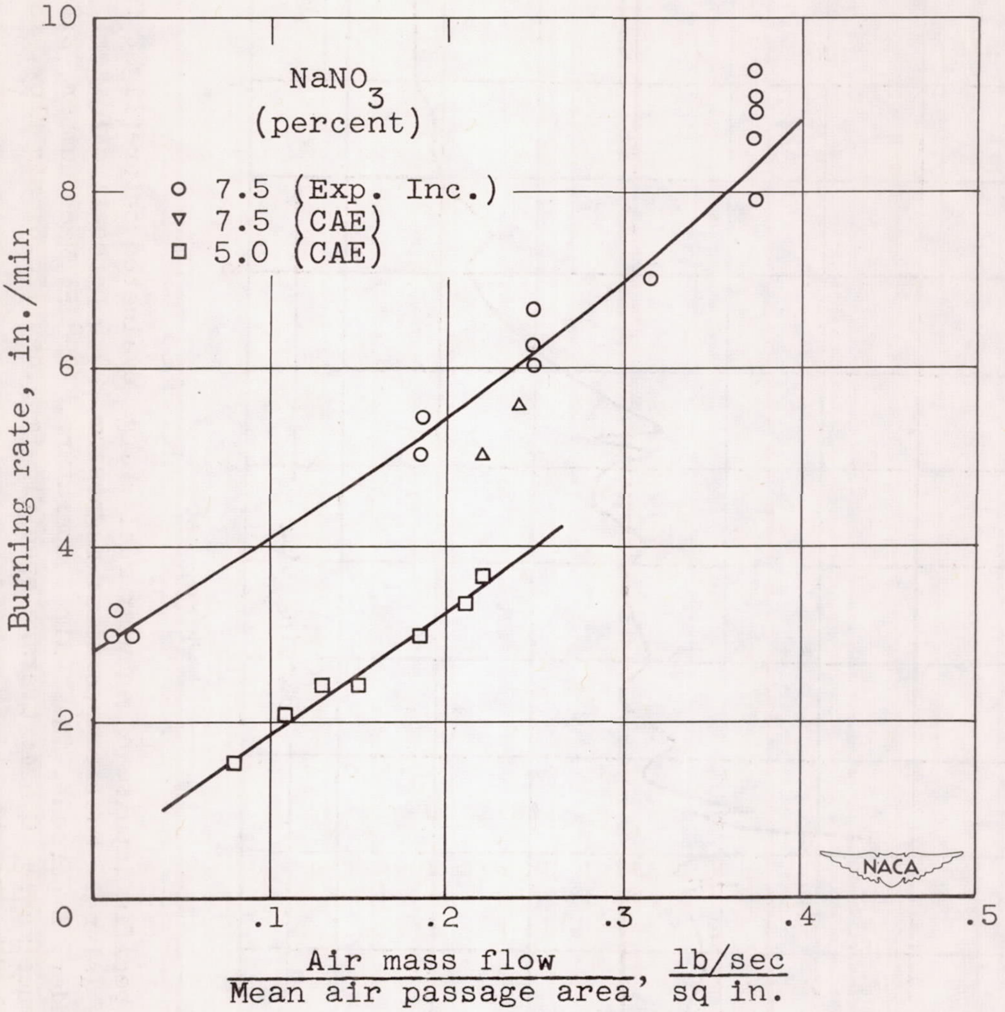


Figure 16. - Effect of air mass flow on burning rate for magnesium. Inlet-air pressure, 27 to 55 pounds per square inch absolute.

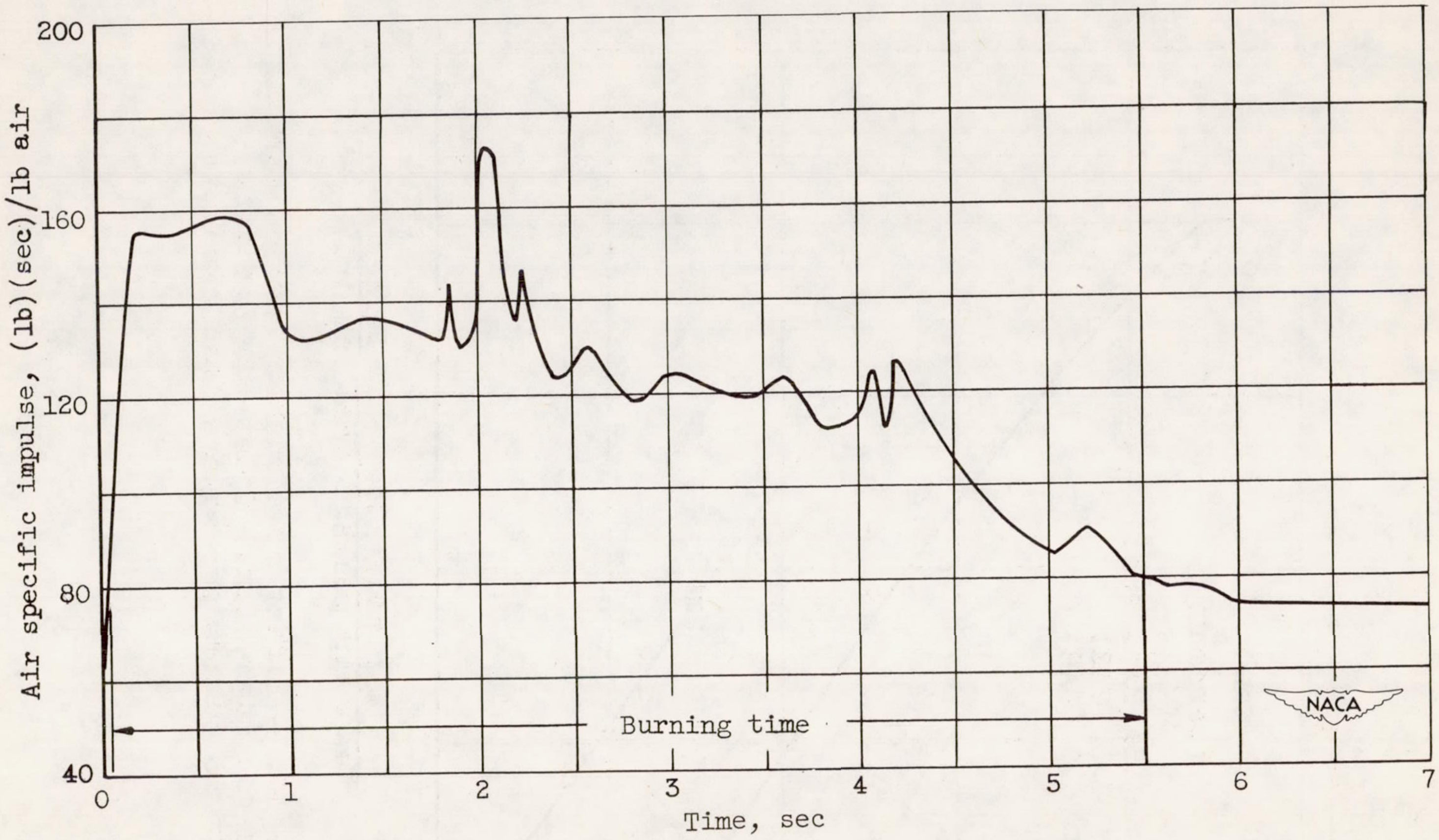


Figure 17. - Air specific impulse of annular fuel charge evaluated on preflight facility at NACA, Wallops Island. Fuel composition: magnesium, 90.5 percent; oxidizer, 7.5 percent; binder, 2 percent; inlet-air temperature, 709° R; Mach number, 2.2; L*, 41; equivalence ratio, 0.594; average specific impulse, 123.6; air flow, 13 pounds per second; total fuel weight, 14.68 pounds.

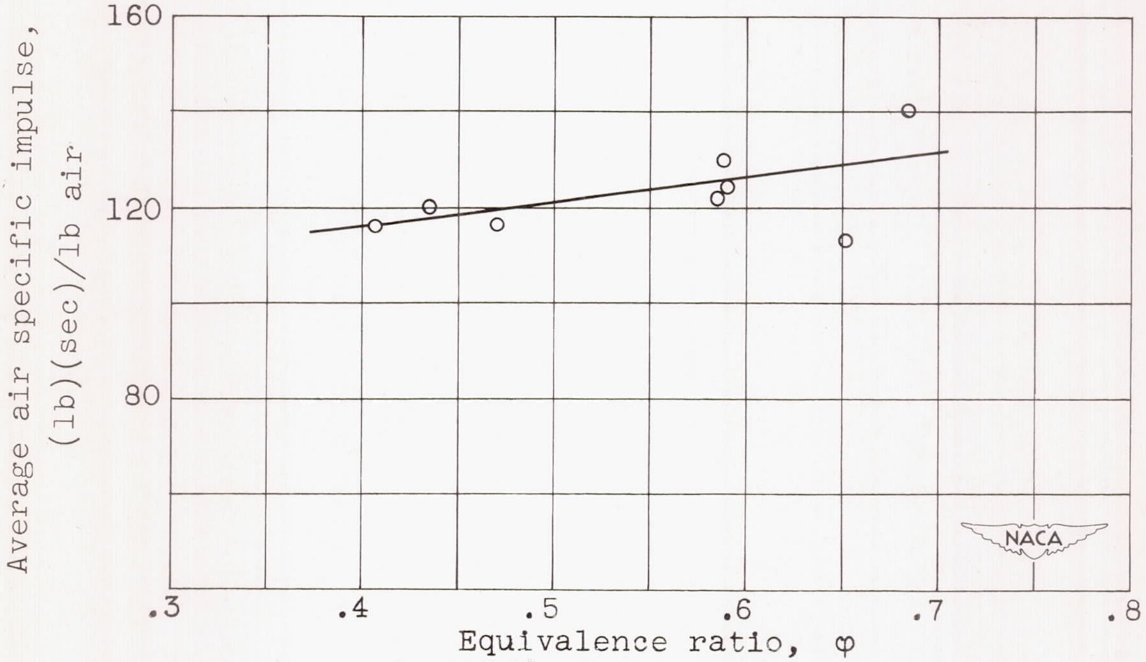


Figure 18. - Average air specific impulse for magnesium solid fuel determined at NACA, Wallops Island. Inlet-air temperature, 679° to 711° R; Mach number, 1.6 and 2.2; L^*, 40 to 51.3.

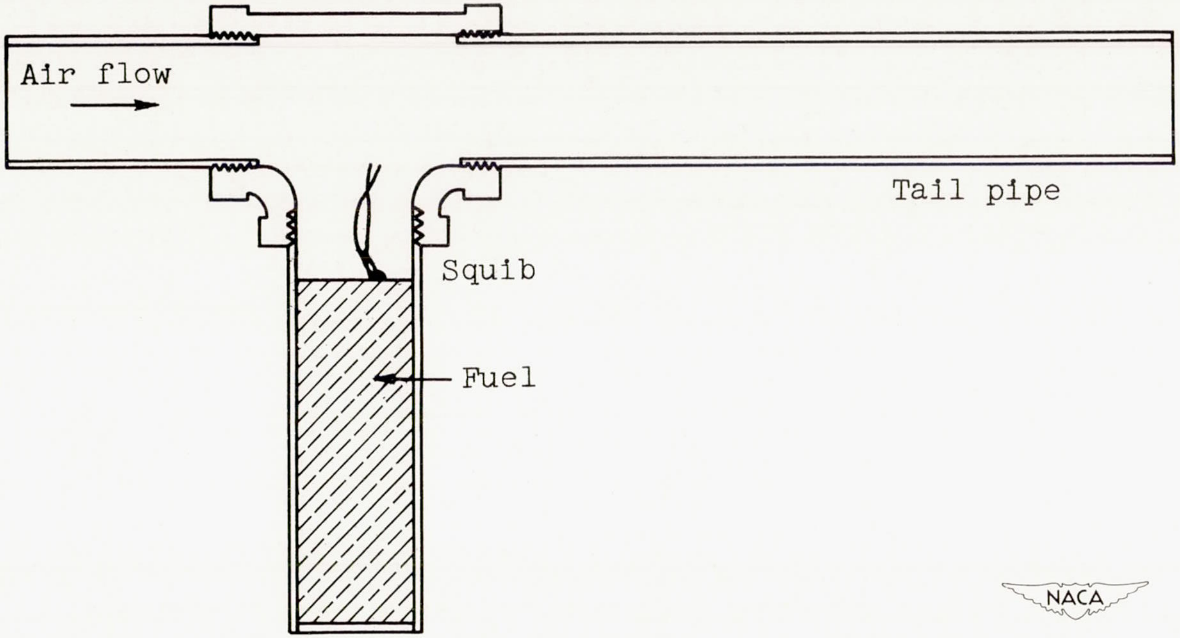


Figure 19. - Schematic drawing of flare burner developed by Experiment Incorporated.

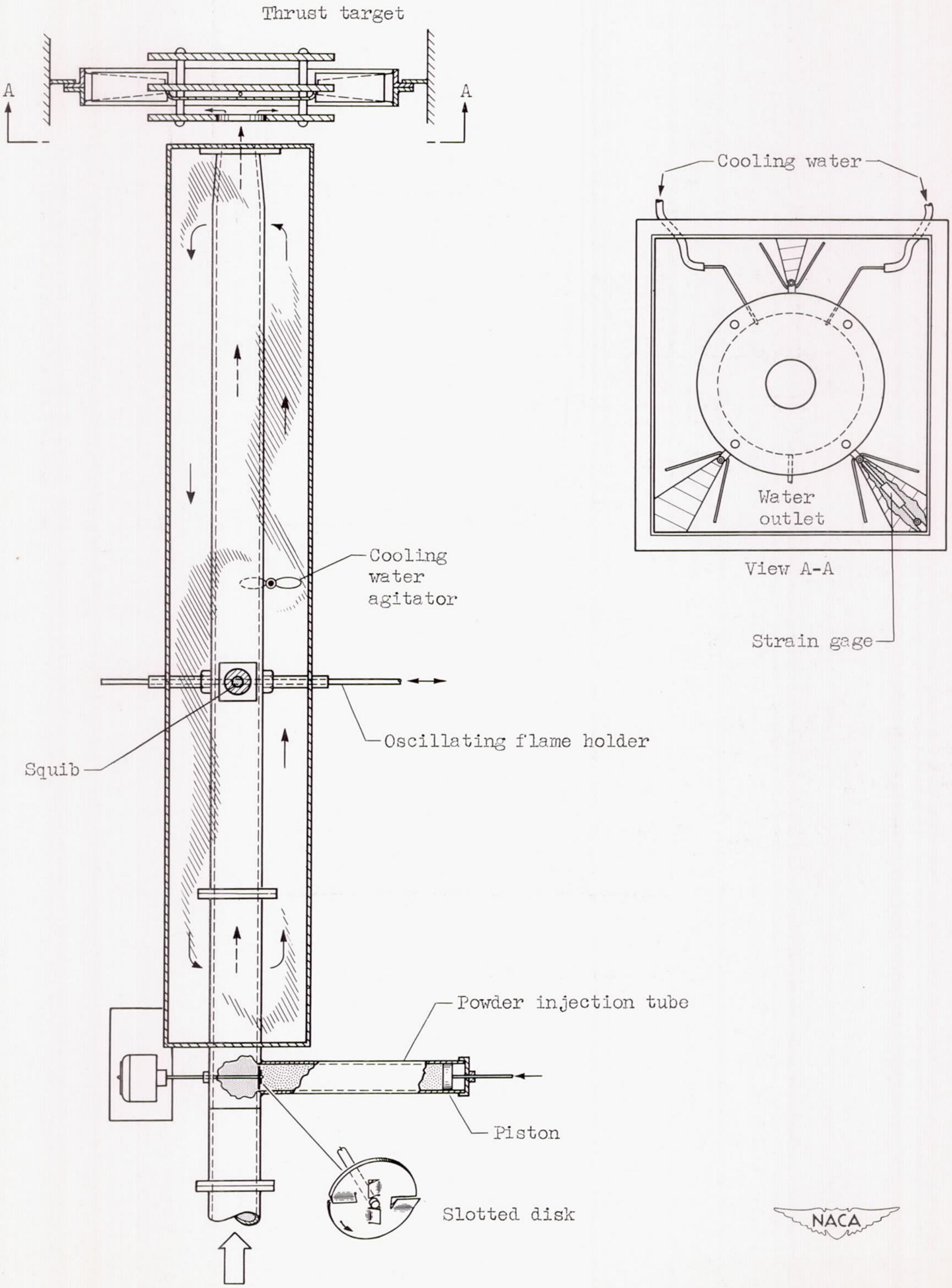


Figure 20. - Experimental setup for 2-inch powder combustor (reference 37).

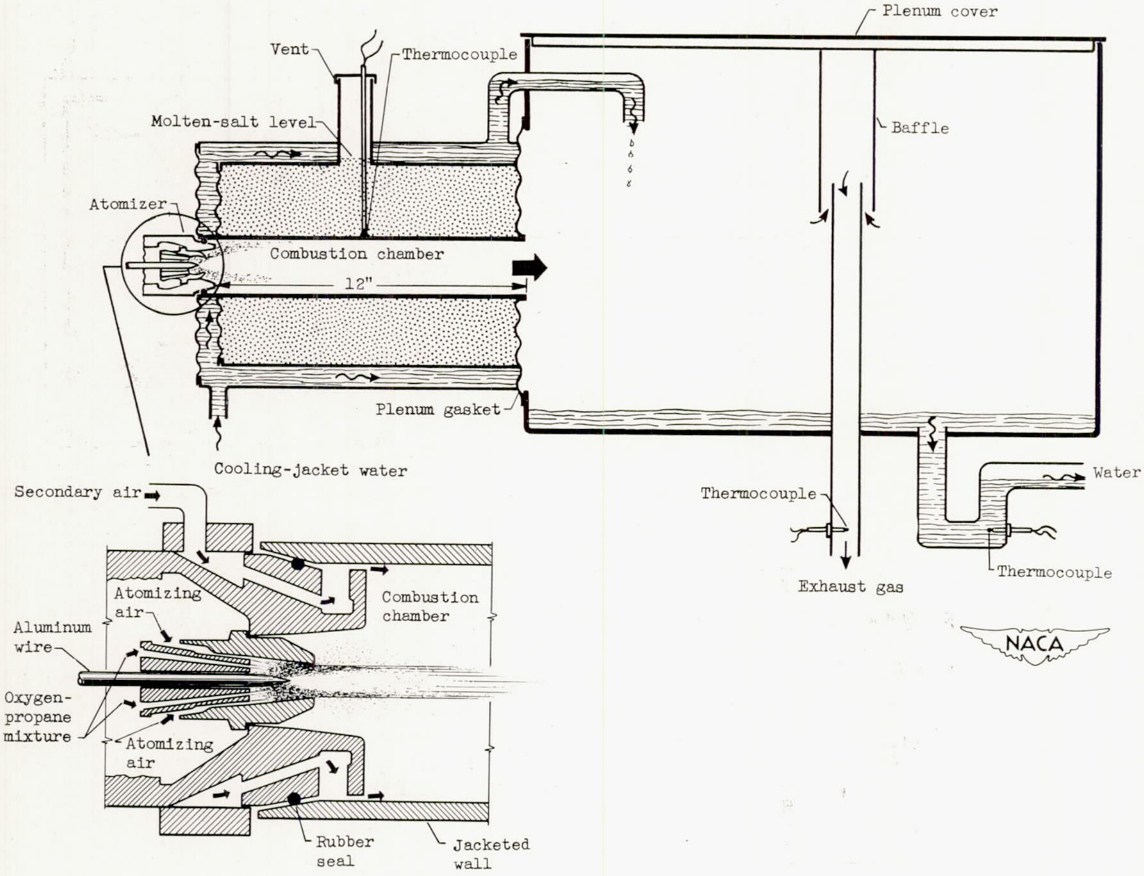


Figure 21. - Experimental setup for NACA 2-inch wire combustor (reference 37).

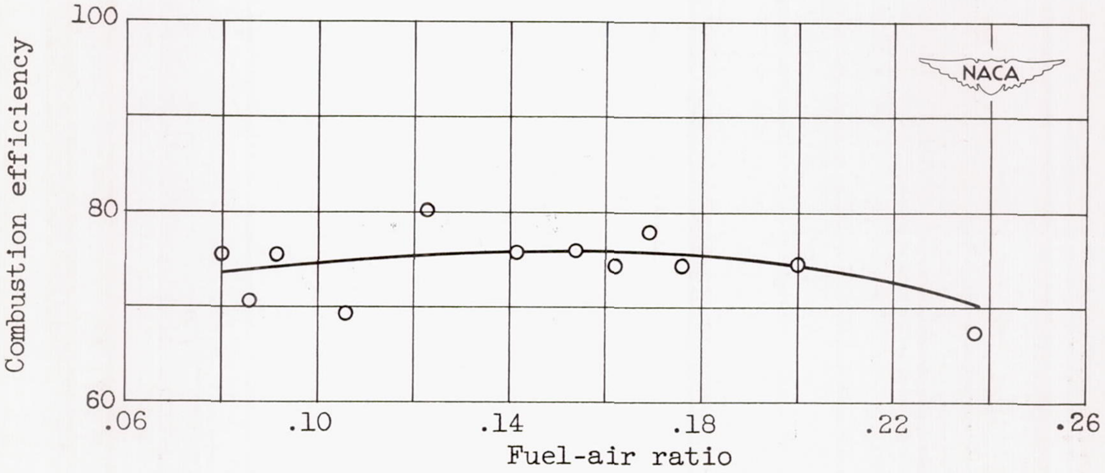


Figure 22. - Combustion efficiency of wire combustor as function of fuel-air ratio. Combustor-inlet pressure, 1 atmosphere; combustor-inlet temperature, 3000° F; combustor-inlet velocity, 115 feet per second.

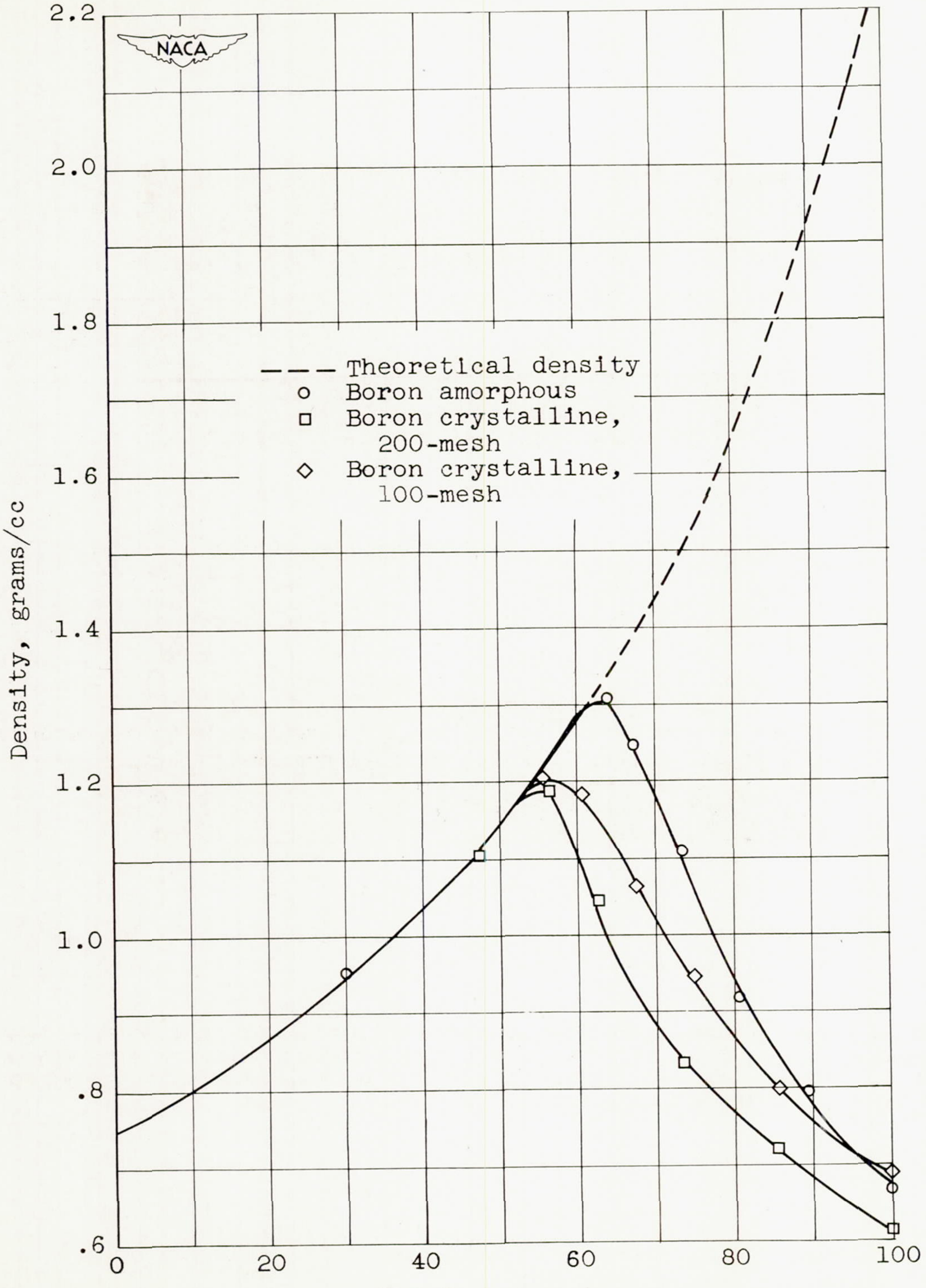
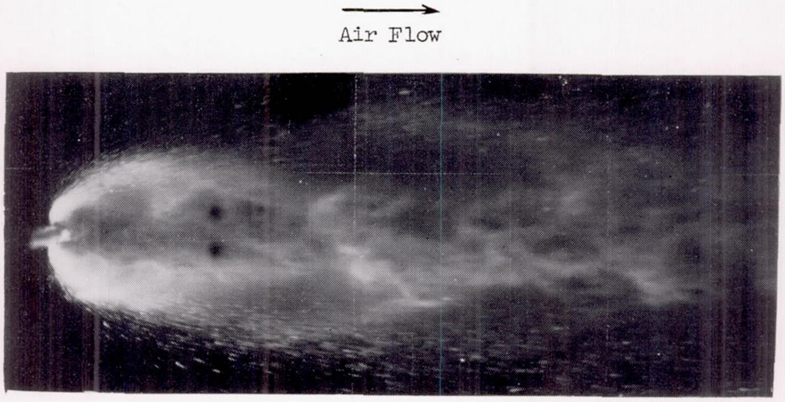
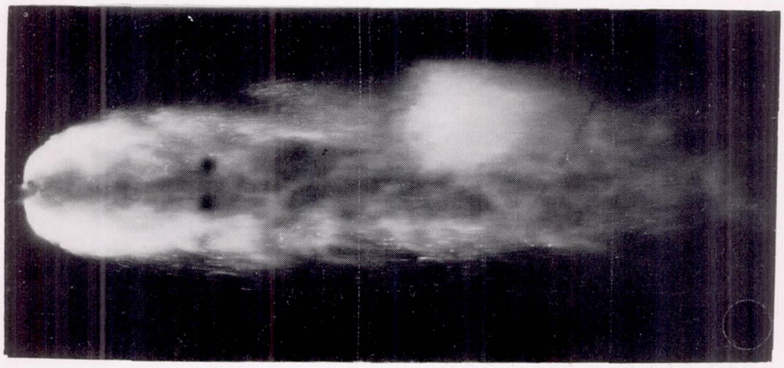


Figure 23. - Density of slurries of boron powder in JP-3 fuel (MIL-F-5624).



(a) 30-percent nonstabilized slurry of magnesium.



(b) Clear MIL-F-5624.

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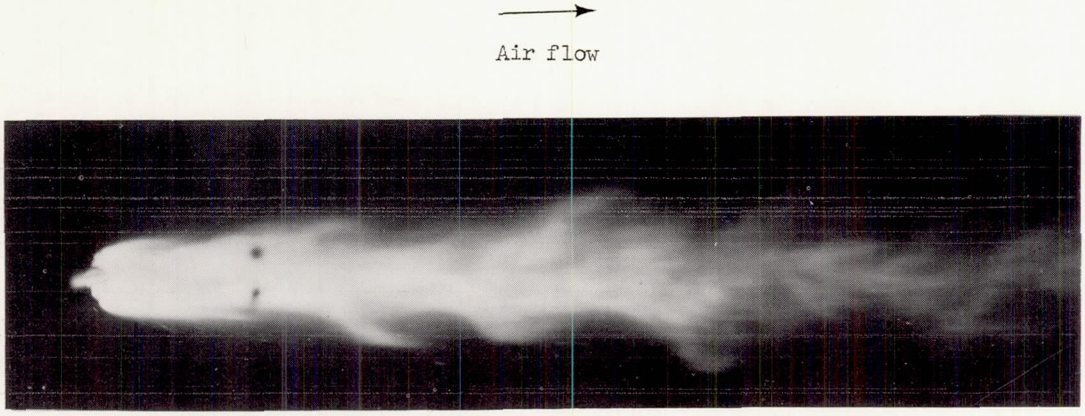
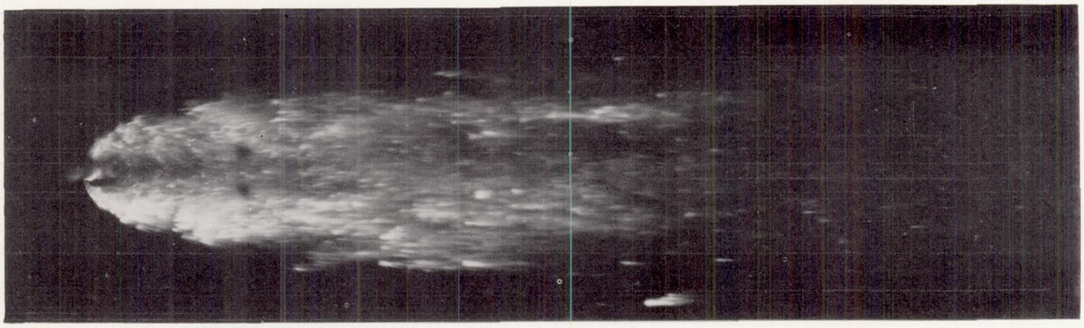
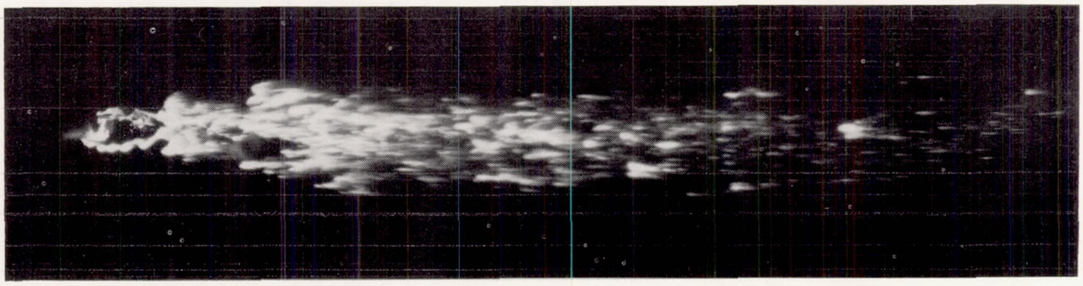
Figure 24. - Spray photographs of clear MIL-F-5624 and a 30-percent nonstabilized slurry of magnesium. Inlet-air velocity, 200 feet per second; fuel jet velocity, approximately 26 feet per second; apparent viscosity, 4 centipoises; inlet-air temperature, 80° F; inlet-air density, 0.05 pound per cubic foot.



(a) Clear MIL-F-5624; viscosity, 4 centipoises.



(b) 30-percent slurry of magnesium containing a gelling agent producing an apparent viscosity of 300 to 400 centipoises.



(c) 30-percent slurry of magnesium containing a gelling agent producing an apparent viscosity of 800 to 1600 centipoises.

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Figure 25. - Photographs showing effect of gelling agents on spray formation. Inlet-air velocity, 400 feet per second; fuel jet velocity, approximately 26 feet per second; inlet-air temperature, 80° F; inlet-air density, 0.046 pound per cubic foot.

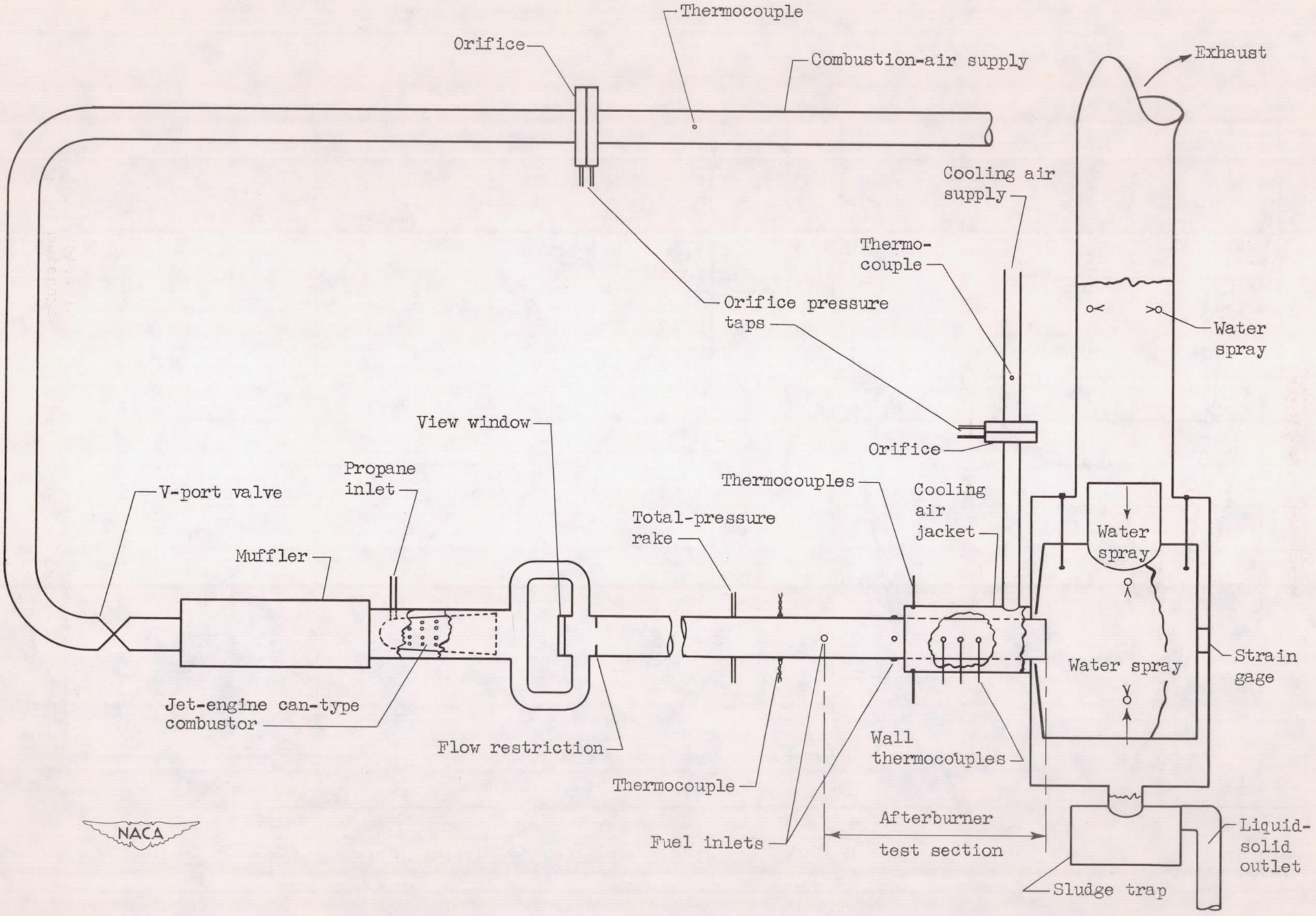
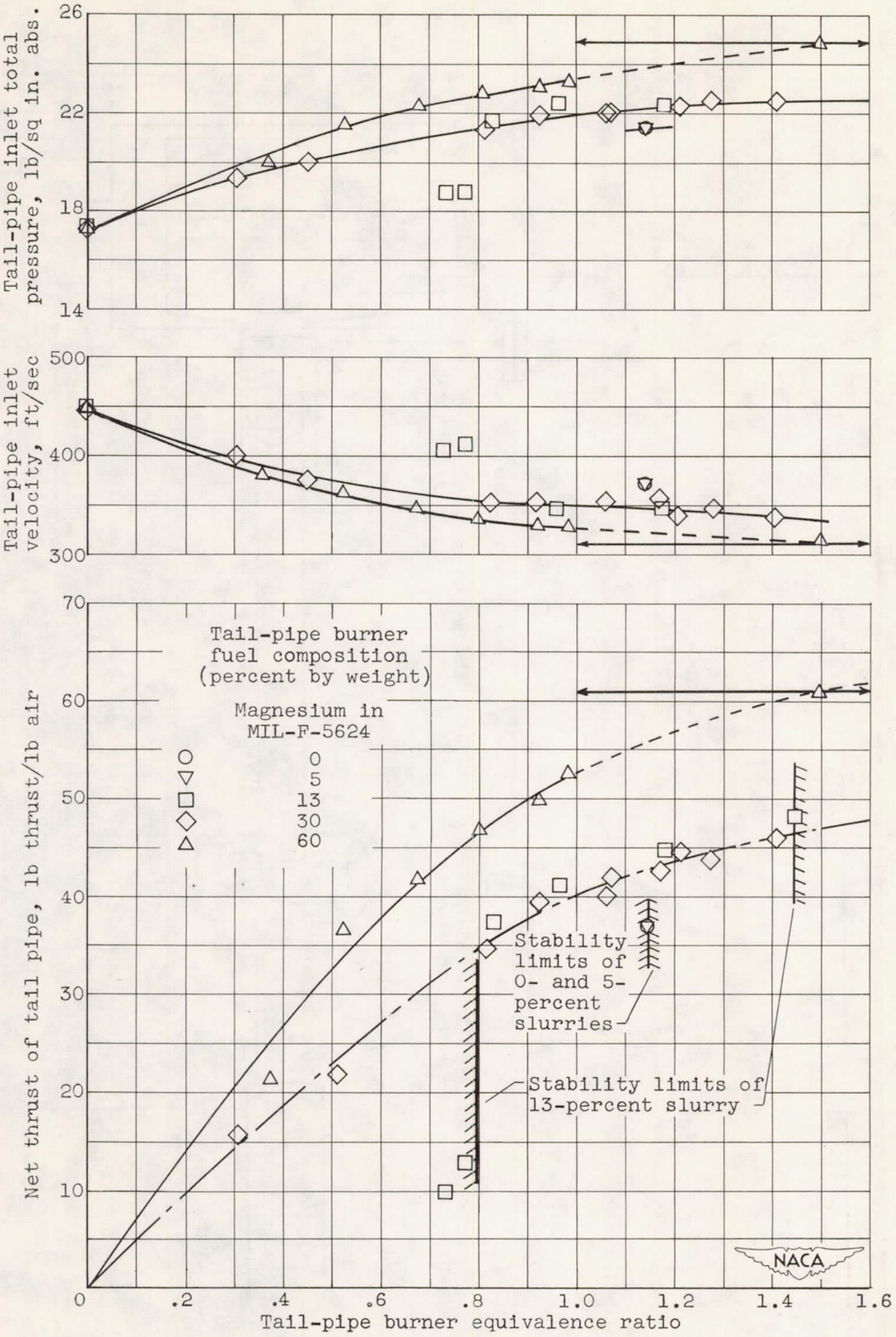
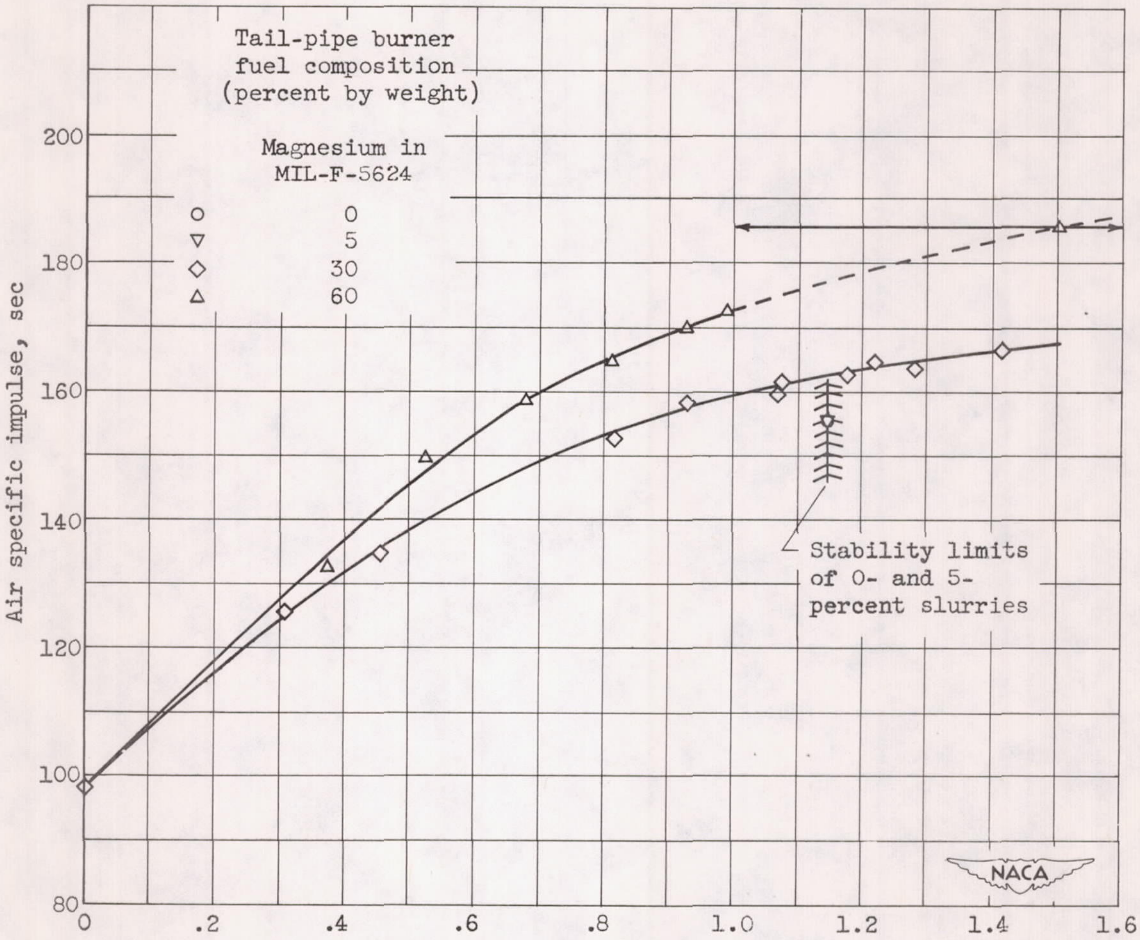


Figure 26. - Six-inch-diameter simulated tail-pipe combustor for slurry fuel (reference 14).



(a) Tail-pipe burner net thrust, inlet velocity, and inlet total pressure.

Figure 27. - Tail-pipe burner performance of slurries containing 0-, 5-, 13-, 30-, and 60-percent atomized magnesium in MIL-F-5624 fuel. (Reference 14.)



(b) Air specific impulse.

Figure 27. - Concluded. Tail-pipe burner performance of slurries containing 0-, 5-, 30-, and 60-percent atomized magnesium in MIL-F-5624 fuel. (Reference 14.)