UNCLASSIFIED

AD NUMBER
AD036130

CLASSIFICATION CHANGES	
TO:	**unclassified**
FROM:	**confidential**

LIMITATION CHANGES

TO:
Approved for public release; distribution is unlimited.

FROM:
Distribution authorized to U.S. Gov't. agencies and their contractors; Administrative/Operational Use; DEC 1951. Other requests shall be referred to Bureau of Ordnance (Navy), Washington, DC 20350.

AUTHORITY

31 Dec 1963, DoDD 5200.10; BUORD/Rand Corp. ltr 29 Mar 1967

THIS PAGE IS UNCLASSIFIED

AD No. 36130
ASTIA
PY

CONFIDENTIAL

APL/JHU TG 154-16
Copy No. 38

RAMJET TECHNOLOGY

Chapter 16

SOLID FUEL RAMJETS

by

ROBERT L. WOLF
and
JAMES W. MULLEN II

Experiment Incorporated

Published by

THE JOHNS HOPKINS UNIVERSITY
APPLIED PHYSICS LABORATORY
Silver Spring Maryland

Operating under Contract NOrd 7386 with
the Bureau of Ordnance, Department of the Navy

CONFIDENTIAL

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18 USC, Section 793 and 794. Its transmission or revelation of its contents in any manner to an unauthorized person is prohibited by law.

Chapter 16

SOLID FUEL RAMJETS

by

Robert L. Wolf and James W. Mullen II
Experiment Incorporated

(Manuscript submitted for publication
December 1951)

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C. SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

TABLE OF CONTENTS

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

16. SOLID FUEL RAMJETS

by

Robert L. Wolf and James W. Mullen II

16.1 HISTORICAL BACKGROUND

The ramjet powerplant for aircraft propulsion, conceived nearly 40 years ago [22, 23], has been available in useful form for less than a decade. Its developers focused their efforts largely on liquid fuels, particularly hydrocarbons of the gasoline or kerosene type. Nevertheless, during the period of resurgent interest occasioned by World War II, there was early recognition that solid fuels might offer certain design and performance advantages.

Although the Germans were chiefly interested in coal and even wood, Sanger and Bredt [36] did suggest the use of metal dispersions to obtain higher flame temperatures and, hence, thrust coefficients. Lippisch [20] and Schwabl [37] were first attracted to solids because of the inherent simplicity of the fuel system in short-duration missiles and artillery or mortar shells. They carried out numerous burner tests with briquetted carbon and natural coal charges, later extending the scope of their work to designs suitable for piloted aircraft.

At Great Britain's National Gas Turbine Establishment, Roberson [33] prepared a theoretical performance survey covering a very large number of solid fuels. Actual experimental work appears to have been confined to aluminum and was conducted

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS TITLE 18, U.S.C. SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

by Wolfhard and Parker [30], Bowling [9], and Fennell [14] at the Royal Aircraft Establishment. Some attention was also given to aluminum hydrocarbon slurries by Mazurkiewicz [25].

In this country, at the Applied Physics Laboratory of The Johns Hopkins University, Berl [8] developed techniques for improving the output of a lean propylene oxide burner through the addition of aluminum and magnesium powders. At the Jet Propulsion Laboratory of the California Institute of Technology, Bartel and Rannie [7] used carbon tubes in flow combustion tests and Alperin [1] considered the problem from a theoretical viewpoint. Damon and his associates at the Bureau of Mines [11] initially investigated coal for ramjet use, but later began to incorporate the light metals in their formulations. Smith [39] extended to ramjet flow conditions the earlier fundamental investigations of Hottel and his Massachusetts Institute of Technology co-workers [44,12,29] into the mechanism of burning carbon spheres. The experimental phases of the program were continued under the direction of Hottel and Williams [3, 4]. Collins and Squiers of the Continental Aviation and Engineering Corporation intensively examined the application of magnesium to booster [24,40] and gun-launched [42] ramjets. To a lesser extent they also employed aluminum, boron, and napthalene in their experimental program. Wolf and others from Experiment Incorporated [46] assisted in the early magnesium fuel and burner development. Two types of propellant charges resulted from this joint program. Either of these gives satisfactory performance under the internal flow conditions obtained in supersonic ramjets and meet to a large extent all other requirements for operational feasibility. Later, the effect of a solid or liquid dispersed phase, such as magnesium oxide, on the aerothermodynamic relations employed in ramjet design calculations was examined [47]. The utilization of aluminum [48] and

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS TITLE 18 U.S.C. SECTIONS 793 AND 794 THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

boron [49] was also investigated. Finally, a solid fuel propulsion test vehicle, after extensive development in free-jet tests [50,53], was successfully flown [38,52] in the velocity range between Mach 1.8 and 2.1 on January 11, 1952. Gammon [15,16,17,18] of the National Advisory Committee for Aeronautics has recomputed the theoretical air and fuel specific impulses of carbon, magnesium, aluminum and boron. Branstetter, Lord and Gerstein [10] from the same organization developed laboratory means for feeding aluminum powder and wire to ramjet burners. At the N.A.C.A. Wallop's Island range Faget and Bartlett [13,28] have carried out free-jet tests on a system similar to that developed in the Continental Aviation program to determine its suitability as a carrier for the flight testing of aerodynamic shapes. Olson and Gibbons recently issued a comprehensive review of the current status of the solid-fuel ramjet field [28]. It is believed that the North American Aviation Company had an interest in this subject, but little published information is available.

Considerable attention has also been given to dispersions or suspensions of metals in hydrocarbon fuels. Under Project BUMBLEBEE Berl [8] at the Applied Physics Laboratory and Anderson [2] at the University of Texas prepared relatively stable suspensions of sodium, magnesium, aluminum, and nickel. In N.A.C.A. investigations, Tower and Branstetter [43] employed a magnesium-hydrocarbon slurry while Gibbs and Cook [19] made boron the dispersed phase. Gammon included these same systems in his theoretical study together with one wherein the metal portion was aluminum [15,16,17]. The Thompson Products Company has also indicated an interest in boron-oil dispersions [31].

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE [illegible] LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

16.2 GENERAL CHARACTERISTICS

Potential Advantages of Solid Fuel Systems

The twofold opportunity of a simpler, more reliable engine having a higher performance is the potent underlying incentive for studying solid fuel ramjet systems. A resume of the arguments, pro and con, indicating the extent to which this objective is realized under present day "know-how" is a principal purpose of this section.

Calculations indicate that sufficient fuel for short (approximately 20 miles) and perhaps intermediate range (100-200 miles) missiles can be stored within the combustion chamber proper without occasioning undue internal drag losses. By this expedient, fuel tanks, pumps, meters, injectors and their associated plumbing, and even the pilot and flame holders, can be eliminated. Means for effecting these component savings in long range missiles (>1000 miles) are not so immediately apparent. The solution, if it exists, must be sought in multiple or externally packaged charges and in high-energy fuels having low burning rates.

In considering the performance to be expected of solid fuels, all pertinent points can be illustrated by limiting the discussion to carbon, aluminum, magnesium, boron, and decaborane. There are, of course, many other possibilities, but the broad technical screening available through Roberson [33] places them in their proper perspective relative to the foregoing selection, especially when economic considerations are taken into account. To facilitate comparison, data for kerosene (ANF-32) will be included.

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

In Fig. 16.2-1, theoretical air specific impulse, S_a, is plotted as a function of equivalence ratio, ϕ, for the several fuels. A more detailed presentation of these calculations is given in the Appendix. The inflection points in some of the curves are associated with phase changes in the exhaust products. It is seen that in thrust-producing capabilities the three metals and decaborane are superior to kerosene. Carbon is slightly inferior but still comparable.

A similar graph, Fig. 16.2-2(a), for theoretical fuel specific impulse, S_f, largely reverses this situation. That is, the metals on a weight basis appear less economical in fuel consumption. Strictly speaking, however, the comparison should be made only at a given level of thrust (i.e. of S_a). In Table 16.2-1, this has been done for $S_a = 170$, the maximum possible with kerosene. On this basis the relative position of boron is not too unfavorable.* The boron hydride alone shows to advantage. Figure 16.2-2(b) extends the comparison to other thrust levels and shows that the advantage held by decaborane increases substantially at lower S_a values.

---

*Recent information indicates that heat of formation of B_2O_3 is somewhat higher than that used in calculations in this chapter. Calculations using a higher heat of formation show boron to have a higher fuel specific impulse than kerosene over the entire S_a range [56].

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW.

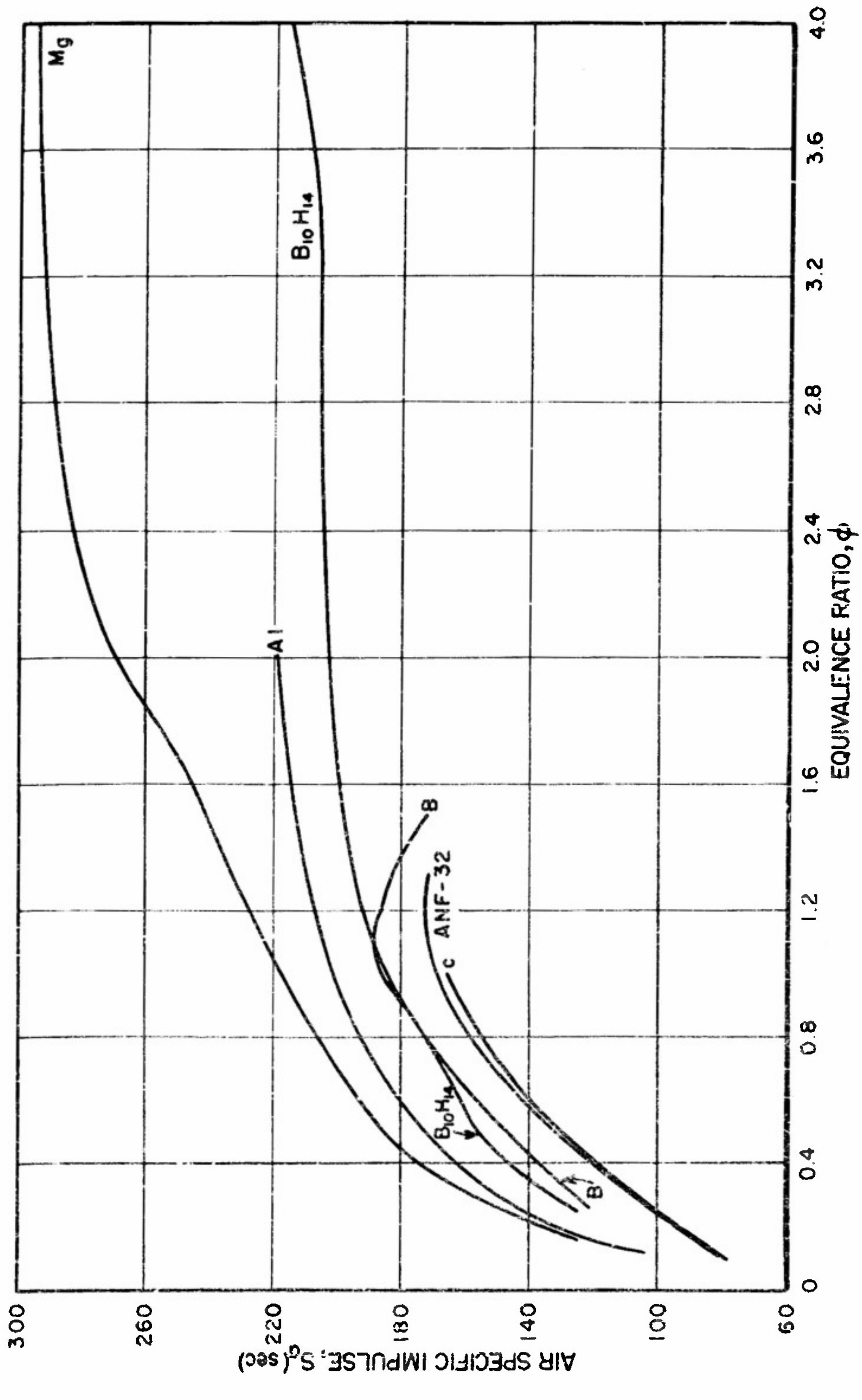


Fig. 16.2-1 AIR SPECIFIC IMPULSE vs EQUIVALENCE RATIO FOR SEVERAL FUELS

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW.

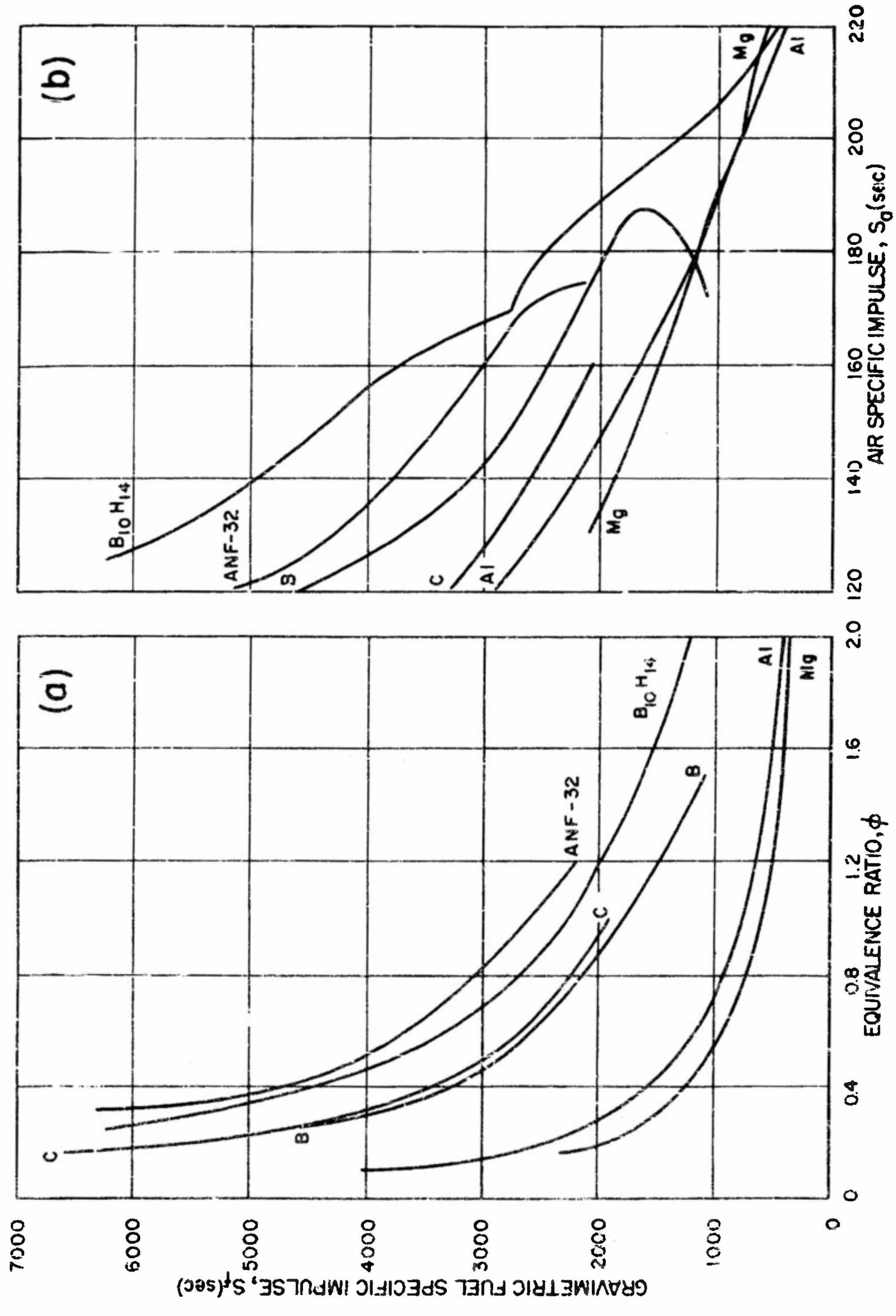


Fig. 16.2-2 GRAVIMETRIC FUEL SPECIFIC IMPULSE vs EQUIVALENCE RATIO AND AIR SPECIFIC IMPULSE

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

TABLE 16.2-1

Theoretical Properties of Various Fuels
at Ø = 1 and at S_a = 170

	Mg		Al		B		$B_{10}H_{14}$		C	Kerosene
Ø	1	0.36	1	0.44	1	0.76	1	0.75	1	1
S_a	220-230	170	200-210	170	187	170	185	170	165	170
S_f	630-660	1,320	785	1,450	1,785	2,070	2,280	2,770	1,900	2,548
BTU/lb air	3,770	1,370	3,470	1,550	2,380	1,810	1,670	1,250	1,230	1,260
BTU/lb fuel	10,800	--	13,300	--	22,700	--	20,650	--	14,150	18,200
lb air/lb fuel	2.87	7.90	3.83	8.61	9.55	12.5	12.36	16.48	11.5	14.8
BTU/ft^3 fuel x 10^{-3}	1,145	--	2,240	--	3,440	--	1,210	--	1,990	931
Flame Temp. °C	3,090	2,230	2,930	2,300	2,840	2,410	2,550	2,220	2,050	1,980
Specific Gravity	1.74	--	2.70	--	2.45	--	0.94	0.94	2.25	0.8
$\frac{(S_f)(\text{Sp.Gr.})}{(S_f)(\text{Sp.Gr. for Kerosene})}$	0.55	1.13	1.04	1.92	2.14	2.48	1.05	1.28	0.99	1.00

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

On the other hand, in considering over-all missile performance, volume is frequently as important a design parameter as weight. Figure 16.2-3(a) gives the product of the fuel specific impulse, S_f, and the fuel density, d, as a function of equivalence ratio. The ratios in the last line of Table 16.2-1 indicate that to maintain a given thrust level (S_a = 170) for a fixed time, less storage space is required for the light metals and for decaborane than for kerosene. With the exception of magnesium, the saving is considerable. The use of Fig. 16.2-3(b) permits comparison at any thrust level.

Practical Difficulties

If the advantages cited above are to be realized, a number of practical difficulties must be overcome. Packaging the fuel within the combustion chamber to eliminate the fuel system components leads to complications as well as simplification. For example, the problem of obtaining fuel-charge geometries having sufficient surface exposed to the air stream to provide the necessary over-all rate of heat release, and yet remain compatible with the requirement of a low internal drag, plagued most of the early investigators. In their reports are numerous drawings of very "unramjetlike" cages and grates for supporting coal charges. On the other hand, if the fuel is fed to the burner as a finely divided powder, either in the pure form or suspended in a liquid carrier, not only is the complexity of the fuel-supply system enhanced over that originally required for liquids but much of the density advantage responsible for a high volumetric heat release is also lost. These same considerations partly apply to a wire-type feeder.

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW.

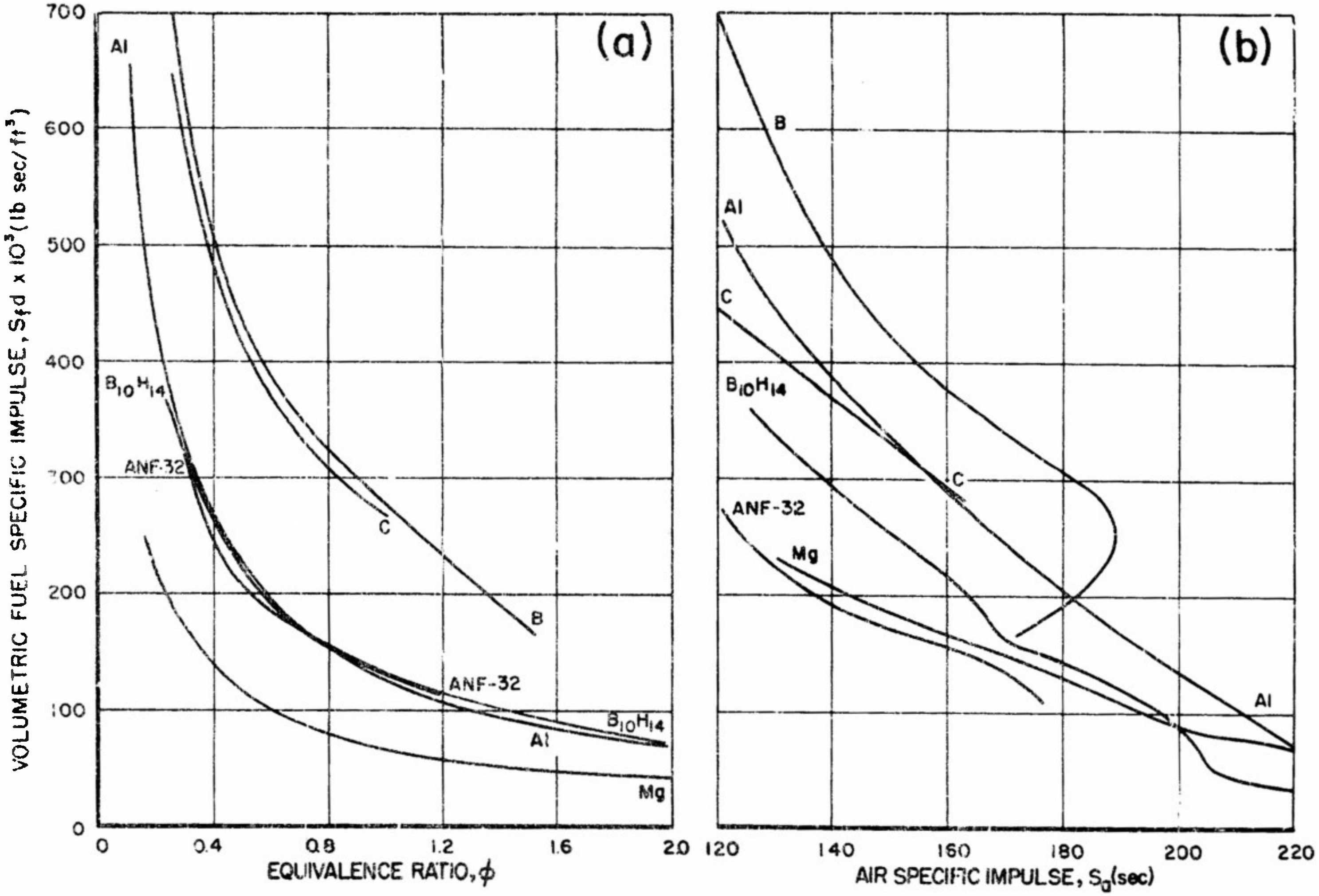


Fig. 16.2-3 VOLUMETRIC FUEL SPECIFIC IMPULSE vs EQUIVALENCE RATIO AND AIR SPECIFIC IMPULSE

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS TITLE 18, U.S.C. SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

When the advocate of solid fuels proudly discarded the fuel meter, he still could not escape the fact that some substitute was required for the function of this useful device. The attainment of delicate thrust control with solid fuels still presents certain problems.

The law of natural perversity seems to apply equally well to solid fuels. The more desirable fuels from the very important aspect of specific fuel consumption are often the least reactive and most troublesome to burn. Easy starting and high combustion efficiencies are more readily obtained with magnesium than with aluminum. The evidence for boron, while currently incomplete, appears to bear out this trend. Even less is known about decaborane, though it should be quite reactive. In the case of aluminum and boron the hard starting, incomplete combustion, and tendency to slag formation, aside from chemical affinity considerations, may lie in the transport processes so important in heterogeneous reactions. These systems can only react (a) by diffusion and/or convection of oxygen to the surface of the solid particle, reacting thereon with subsequent outward transport of the oxide to leave fresh material for further oxidation, or (b) by evaporation of the solid from the surface of the particle to the surrounding air followed by essentially vapor-phase reaction. Table 16.2-2 lists the melting and boiling points of several fuels and their oxides together with the approximate peak flame temperature associated with the combustion process. The transition points, like much of the other thermal data in these cases, are subject to some uncertainty. The high boiling point of boron suggests that the first mechanism, i.e., diffusion of oxygen to the boron surface, is the more likely. Further difficulty is indicated by the low melting point and high boiling point of the oxide; that is, an adherent glassy film of this

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

TABLE 16.2-2

Transition Temperatures

	B	Mg	Al	C	$B_{10}H_{14}$
Flame Temp., °C	2840	3090	2930	2050	2550
Fuel					
M.P., °C	2300	650	660	4350*	100
B.P., °C	2550	1120	2327		213
Oxide					
M.P., °C	450	2800	2050	-78*	450
B.P., °C	2250	3500	2250		2250

*Sublimes

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW.

material may seal the surface of the metal particle against subsequent reaction. In contrast, the highly efficient magnesium combustion which has been achieved experimentally ties in with the low boiling point of that metal. The magnesium particles probably evaporate at an early stage so that the main reaction is actually carried out in the vapor phase. In addition, under most circumstances the high melting point of the oxide would lead to a brittle, friable coating easily dispersed by aerodynamic forces. Under this hypothesis aluminum should occupy a position intermediate to boron and magnesium in difficulty of combustion, which is largely in keeping with the observed situation. Carbon offers an example of a high "boiling" fuel which maintains a clean surface through the extreme volatility of its oxides.

The problem of ignition in solid fuel charges has its own peculiar difficulties. Some of the early coal burners took several seconds, even minutes, to bring up to a point of self-sustaining combustion. An ignition lag of tenths of seconds or less is more in line with the starting requirements in many ramjet applications.

A number of the more interesting solid fuels have an exhaust stream containing a finely dispersed solid or liquid phase. Other than how to handle their effect in fluid mechanical expressions, they lead to heat transfer problems. No longer held down by the low radiant component of the transparent combustion products of conventional hydrocarbon fuels, wall temperatures can become dangerously high, especially if advantage is taken of the maximum flame temperatures available with certain metals. Measured losses through the combustion-chamber wall of a 2-inch magnesium burner have been 12 to 25 per cent of the total heat release [46]. This is roughly two to five times greater than observed with hydrocarbon fuels. On the

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

other hand, Tower and Branstetter [43] have reported a lower transfer to the walls when a given burner was run on hydrocarbon-magnesium slurries than when run on the pure hydrocarbon. Presumably, this was due to the insulative effect of the oxide coating built up on the inner surface of the combustion chamber. On a visit to Wallop's Island, the writers observed a thin, continuous film of oxide firmly adhering to the walls of the N.A.C.A. 6-inch magnesium burner [32]. The phenomenon, however, does not seem to occur to the same extent in their own 6-inch tests at Experiment Incorporated. Obviously it would be desirable to induce the build-up of this self-insulating layer with some degree of reliability. All in all, further study of the heat transfer processes in solid fuel ramjets is indicated.

The same exhaust condition, high temperatures and smoke, is the source of another concern: i.e., interference with guidance or telemetering signals. Since no work has been done along these lines on the systems of immediate interest, an investigation is again indicated.

Finally, there is the matter of economic considerations. The better fuels are not only the least reactive, but they are the most expensive. Finely powdered magnesium can be bought today for $2.00 a pound, aluminum for $0.27, impure boron for $12.00 to $15.00, although the pure element is quoted between $250.00 and $400.00 per pound. There have been informal indications that this might be reduced in quantity production. Even so, one manufacturer has pointed out the improbability of the price of any suitable fuel ever dropping below $1.00 a pound [45]. In the case of decaborane any meaningful price would be difficult to establish today. For missile application, the position taken by Longwell [21] is probably sound. That is, if one considers how expensive guided missiles are on both a

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS TITLE 18, U.S.C. SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

total and a unit weight basis, and the importance of insuring a successful mission, a fuel that offers operational advantages should not be eliminated on a price basis unless the fuel cost approaches the cost of the missile.

Applications

To be valuable any consideration of applications should be based on those characteristics wherein solid fuel ramjets possess superiority over other forms of propulsion. Thus, in the earliest German work mortar and artillery shells [20] would appear to be a more appropriate subject for investigation than piloted subsonic aircraft [36]. Mechanical simplification of the fuel supply and combustion systems, with the accompanying increase in reliability, is an obvious asset in all of the suggested applications and, therefore, will not be touched upon again.

Pursuing this only logical approach that the characteristic should determine the application, the high air specific impulses available with certain solid fuels suggest some form of booster device or self-accelerating ramjet [34,40,24]. Where the missile end use can tolerate relatively long acceleration periods, the initial velocity can be achieved by release from conventional aircraft. The boost to final design velocity can then be achieved by a high thrust, solid fuel charge simply packaged within the combustion chamber of a conventional hydrocarbon ramjet. Alternatively, a small rocket can be used to establish the initial velocity and the second stage boost be accomplished as before, with the additional possibility of an externally mounted engine.

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C. SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

The high volumetric specific fuel impulse of many solid fuels, particularly in the lower thrust ranges comparable to hydrocarbon performance, provides an opportunity for the development of useful midcourse sustainers [51,35]. The feasibility of this application, of course, also depends on the weight, mechanical complexity, and external aerodynamics of the mechanism required to incorporate the sustainer drive in the main missile.

Boron or certain of its solid hydrides more effectively illustrate the characteristic of high volumetric specific fuel impulse and open the question of long-range missile applications. Unfortunately, only cursory investigations have been made of this possibility. The problem is not simple, gravimetric specific fuel impulse and methods of mechanically handling the fuel charges being only a few of the other influential factors.

High stagnation temperatures with resultant overheating of the fuel has been one deterrent to flight at speeds much in excess of Mach No. 3. Metal fuel charges may obviate at least part of this difficulty in the development of hypervelocity ramjets [6].

Experimentally, it has been shown that the combustion efficiency of magnesium-fueled burners is relatively insensitive to lowered inlet pressures. Extreme altitude ramjets may be possible through the utilization of this characteristic.

Many solid fuel charges have excellent mechanical properties, e.g., compressive strength, and, therefore, can withstand the stresses of a short boost period. For example [42], powdered magnesium briquettes have been tested successfully at accelerations up to 26,500 g. Because of this it appears feasible to design gun-launched ramjets more reliable than those originally suggested by Tromsdorf. Preliminary calculations show that even with diffuser efficiencies as low as

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

40 per cent a muzzle velocity of 4000 fps can be sustained and even increased during the flight of the projectile [6]. Other studies show that roughly three pounds of a solid fuel would propel a 20-pound low velocity mortar shell nearly 9000 yards [6]. Continental Aviation and Engineering Corporation has indicated that artillery shells having ranges on the order of 150 to 200 miles may be within reach. One modification of the solid ramjet charge can be employed to reduce base drag in more conventional shells, thereby providing worthwhile increases in range [5].

An interesting application to underwater ramjets stems from the observation that certain light metal charges "burn" as well under water as in an air stream in accord with the reaction:

$$2Al + 3H_2O \longrightarrow Al_2O_3 + 3H_2 + 1,106,000 \text{ BTU/ft}^3 \text{ Al.}$$

The same fuel could also be confined to generate gas for some form of turbopropeller drive.

In the foregoing discussion only generalized applications based on the chemical and physical properties of solid fuel charges were indicated. The weapons designer will see for himself numerous combinations of these features provocative of more detailed consideration in air-to-air [54,55], air-to-ground, ground-to-air, ground-to-ground, intercontinental, and other missile fields. Flat-trajectory, high-penetration anti-tank ordnance is suggested. Simple projectiles for saturation bombardment at greater than rocket ranges are apparent. The employment of solid ramjets for the routine testing of aerodynamic forms as attempted by N.A.C.A. has considerable potentiality. These and numerous other opportunities await exploration.

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW.

16.3 BURNER PERFORMANCE

Fuel Charges

Two types of fuel charges [40,46] are available in a sufficiently advanced developmental state to warrant consideration in current application studies. Both types employ finely powdered fuel, mixed with small amounts of an inorganic oxidizer and molded under pressure in the desired geometric shape. A low percentage of some organic binder is incorporated to improve the physical strength of the briquette. This general formulation was tested by the Germans [20,37] almost at the outset of their program. They did not, however, carry the work to its logical conclusion, having been discouraged by the extensive fracture of the charge during burning, which resulted in over half the fuel being discharged as large unburned fragments.

The first type, known as the annular charge, is illustrated in Fig. 16.3-1(a). A more versatile modification, the split-flow annular charge [53,54], is shown in Fig. 16.3-1(b). In either case, a rapid-burning pyrotechnic composition is integrally molded to the upstream face of the fuel charge. This charge is touched off with a commercial black-powder squib imbedded therein to supply instantaneously the ignition energy for the main charge. The average delay from the moment of closing the firing switch to development of full thrust is on the order of 0.2 second. Alternatively, part of the ignition charge and squib can be mounted in the form of a flare external to, but directed at, the rapid-burning upstream face of the main charge. This technique minimizes the possibility of fracturing the main charge by the initial explosion. The flame from the fast-burning booster layer traverses the passage through

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C. SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

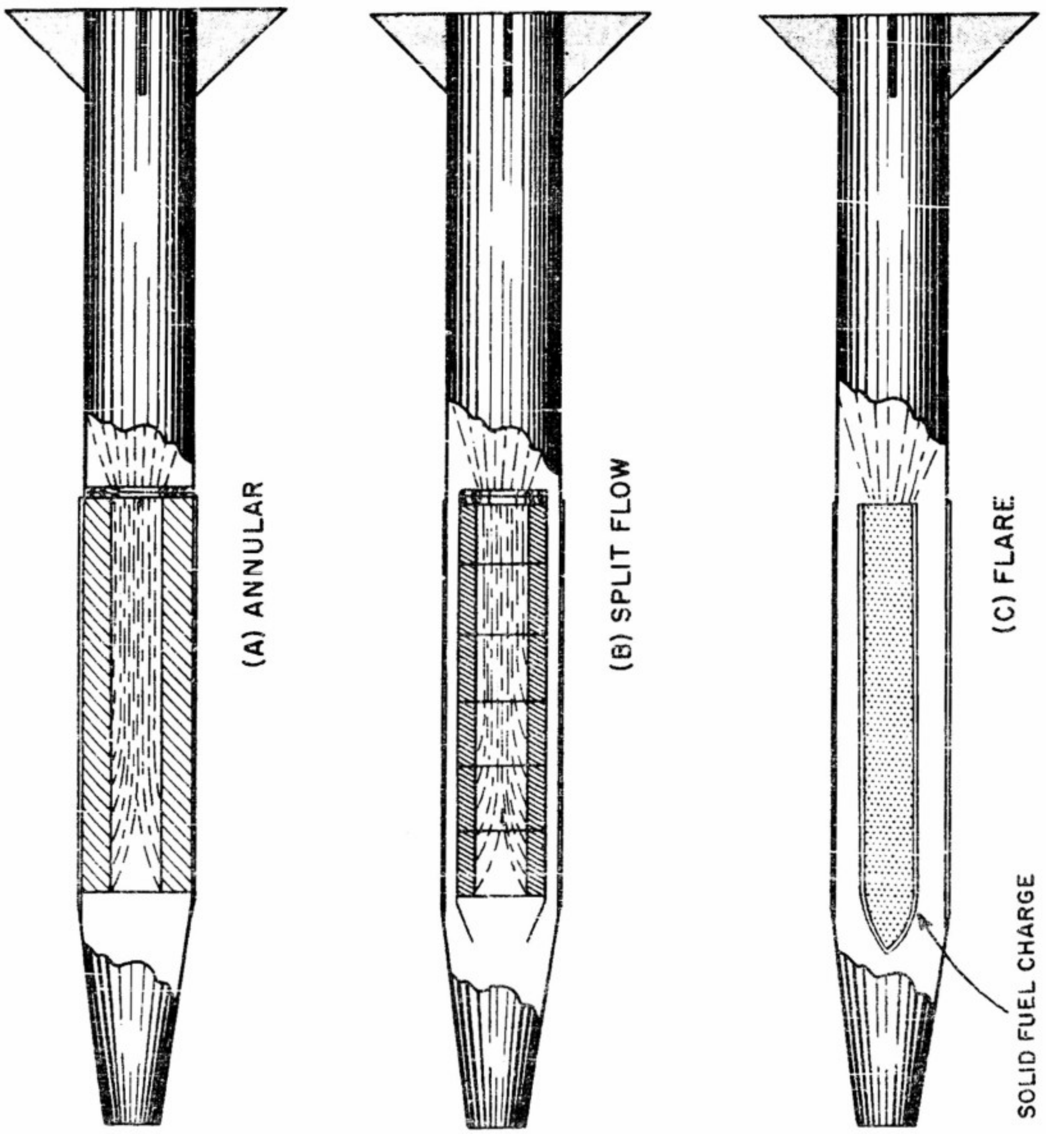


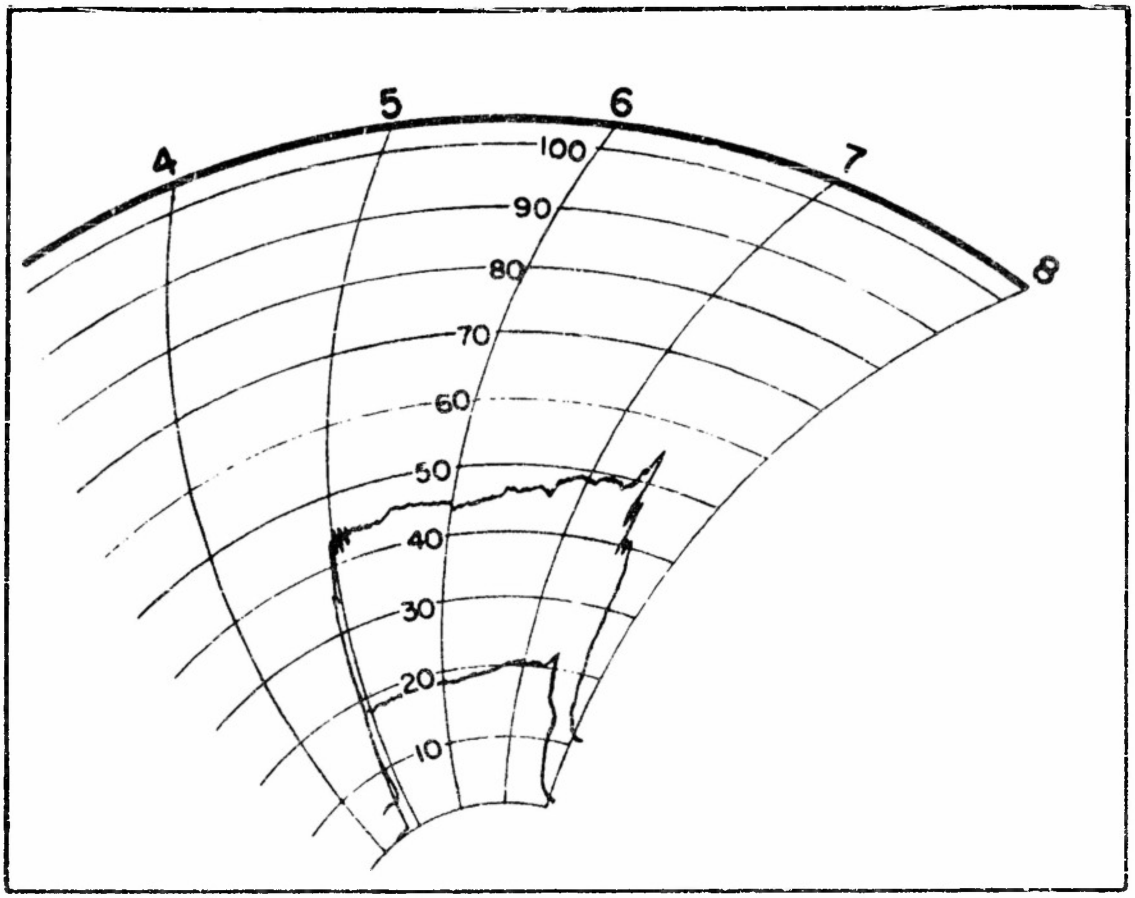
Fig. 16.3-1 THREE TYPES OF SOLID FUEL CHARGES

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW.

the center of the annular charge, igniting the inner surface over its entirety. The principal combustion then ensues radially and progressively toward the outer wall. Only when a very thin shell of fuel remains does the charge break up. The fuel losses attributable to this cause are minor and in small burners seldom exceed more than about 5 per cent of the total charge. It does, however, lead to a moderate roughness in the last second or so of burning, as can be seen on a typical thrust chart reproduced in Fig. 16.3-2.

The key to successful performance of these charges is the small content of inorganic oxidizer. Although the quantities present are insufficient to sustain combustion in the absence of the air stream, they do serve to stabilize the flame at the surface of the charge and possibly to sputter hot particles (and vapor) of unburned fuel toward the center of the duct for better mixing and contact with the atmospheric oxygen. It is this latter function of "built-in" fuel injection which forms the basis of the second or flare-type charge shown in Fig. 16.3-1(c). Now the oxidizer content has been increased to the point where the surface combustion, though still very fuel-rich, is self-sustaining in the absence of air. Upon ignition at the open end of the container, the surface recedes longitudinally in the so-called "cigarette-burning" manner. Very hot fuel particles, or under some circumstances, fuel vapor are ejected with considerable velocity into the main air stream. The problem of controlling the shift in center of gravity of a missile during burning appears at first sight more serious with the flare than with the annular charges. The internal burner drag with all three types of charges seems to be in the range of 4 to 8 inlet dynamic heads.

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW



UPPER LINE ~ lb/in^2(gouge) IN BELLOWS ON THRUST STAND

[lbs thrust = 1.14 x lb/in^2(gouge)]

LOWER LINE ~ FLAME PRESSURE lb/in^2(gouge)

TIME SCALE = 2.5 SECONDS PER DIVISION

Fig. 16.3-2 TYPICAL THRUST CHART

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

In the development of these charges the principal effort has centered on the use of powdered magnesium as fuel in conjunction with sodium nitrate as oxidizer. Linseed oil was ordinarily employed as the binding agent. Molding pressure was 1200 lb/in^2 leading to a charge density of 1.35 as compared to 1.74 for the pure metal. Where extremely tough charges are required, higher pressure molding has produced charge densities between 1.5 and 1.6 [42]. Efforts to burn pure aluminum powder [48] have been complicated by poor ignitability, flame "blowout" after ignition, low combustion efficiency, and slag formation in burner components or in the nozzle. One explanation for these difficulties has already been offered. The most practical remedy uncovered to date appears to lie in admixture with magnesium and use of higher nitrate concentrations. Certain additives, such as sulfur, have been found beneficial, whereas the normal alumina fluxing agents, such as cryolite, have had little effect. Although these "diluted" aluminum preparations do not permit full realization of the higher volumetric heat content of this fuel, they nevertheless offer an improvement of at least 35 per cent over the better magnesium fuels in this respect. Figure 16.3-3 outlines the variation in volumetric heat content of charges containing different magnesium-aluminum ratios as well as sodium nitrate contents. The best all-round experimental mixture contains 5 per cent of sulfur and is also included on the chart. Charge densities are roughly 70 per cent of the pure metal. Efforts to burn crude amorphous boron (86 per cent pure) have met with similar, but even more severe, difficulties. One apparent drawback is that in using amorphous boron the charge density seems limited to the relatively low region of 50 per cent of the bulk density of the element. This obstacle can probably be overcome with crystalline boron powder if such becomes available.

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

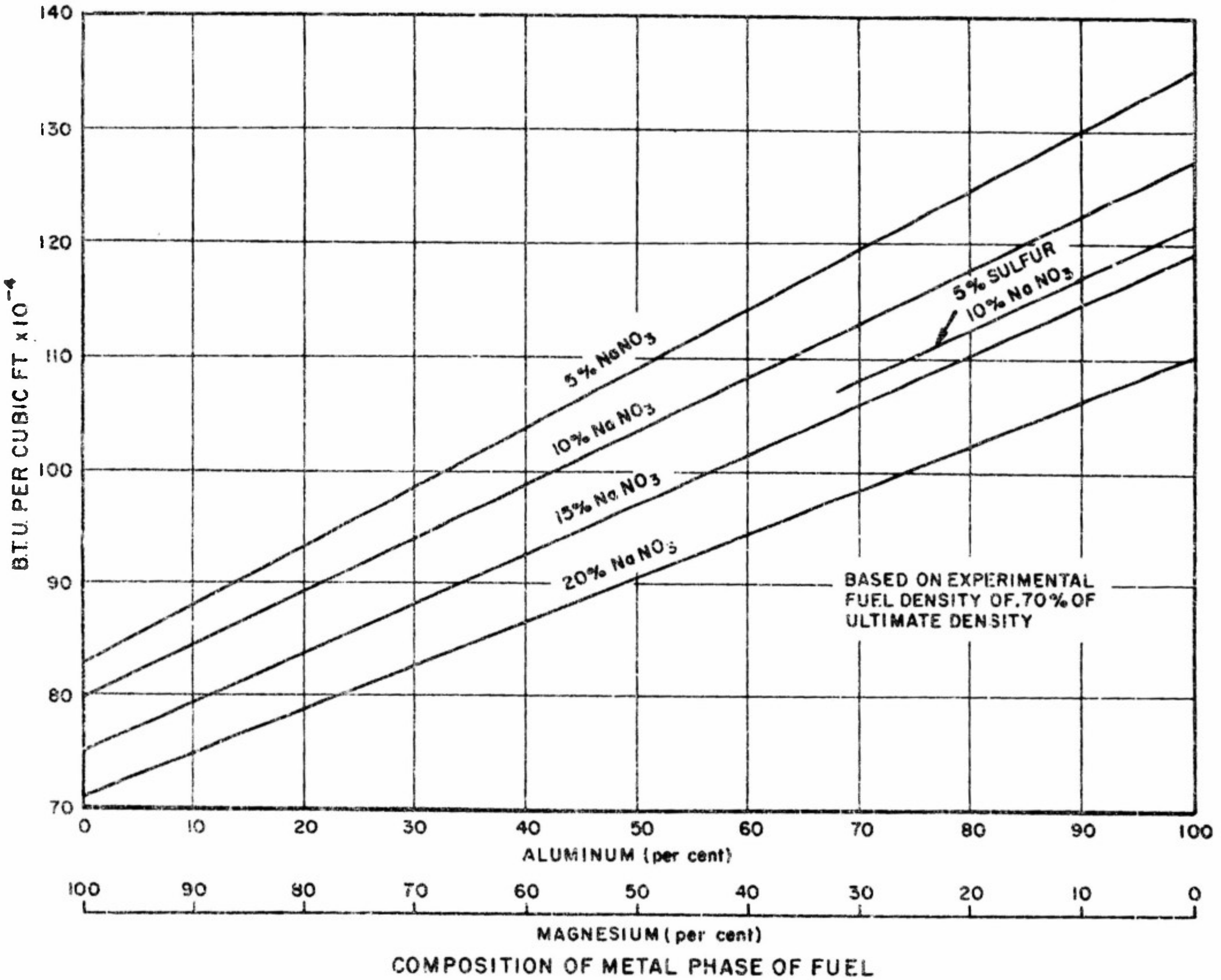


Fig. 16.3-3 HEAT OF COMBUSTION -- BTU PER CUBIC FOOT vs FUEL COMPOSITION FOR VARIOUS MIXTURES OF ALUMINUM, MAGNESIUM, AND SODIUM NITRATE

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW.

The entire study of fuel types has been handicapped by the lack of a laboratory equipped for the preparation of powdered alloys and intermetallic compounds. Small amounts of calcium are said to lower the "ignition temperature" of magnesium. Other combinations undoubtedly offer other advantages, particularly in developing satisfactory fuels based on aluminum and boron. The possibilities inherent in alloys can never be explored as long as formulation is limited to mechanical mixtures of commercially available powders.

Linear Burning Rate

Of prime interest to the ramjet designer is the thrust coefficient of the over-all engine. A basic determinant of this quantity is the burner air specific impulse and this in turn depends strongly on the air-fuel ratio or more conveniently the air-fuel equivalence ratio. In conventional ramjets the fuel meter controls and regulates these three important parameters for various design and flight conditions. In solid fuel ramjets the fuel-metering function is an inherent property of the fuel charge which is manifested as its linear burning rate. Thus, the weight flow of fuel, m_f (lbs/sec), is given by the product of the linear burning rate, V_l (in/min), the total area of the burning surface, S (in^2), and the density, d, of the charge in lbs/ft^3, or:

$$m_f = \frac{V_l S\ d}{103{,}680}$$

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW.

In annular charges S is the surface area of the internal passage, but in flare charges it is the cross-sectional area. The linear burning rate is also important when taken together with charge geometry in determining the burning time or duration of the flight.

In general, the linear burning rate is determined by formulation variables: e.g.,

1. Fuel type,
2. Size and shape of fuel particles,
3. Type and concentration of oxidizer,
4. Particle size of oxidizer,
5. Type and concentration of binder, and
6. Density of charge.

and by burner-design variables, e.g.,

1. Equivalence ratio,
2. Charge temperature, and
3. Air mass flow per unit cross-sectional area of central air passage (annular charges).

Considering the first group, few significant comparative data are available today on the differences in basic burning rates of various pure fuels. In order to get aluminum to burn at a satisfactory combustion efficiency, it has to be formulated in a 4-to-1 or possibly a 6-to-1 ratio with magnesium and "doped" with 10 per cent sodium nitrate and 5 per cent sulfur. That this charge has roughly the same linear burning rate as a magnesium one containing only 5 per cent sodium nitrate is but rather weak evidence for aluminum having a lower basic rate. In any event, the designer will probably select the fuel on a thermodynamic basis so that discussion of the other formulation variables is more to the point.

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW.

Under present supply conditions the size and shape of the fuel particle is also a minor factor. Roughly speaking, the burning rate might be expected to increase with a decrease in particle size. The observed change, with magnesium at least, was insignificant between -70 and -200 mesh. As to particle shape, ground magnesium with its rough irregular particles (compared to the regular spheres of the atomized material) burned poorly. The rough particles, however, compact to give a harder charge, and the decrease in combustibility may have been due to the density effect described later.

When compared on the basis of available oxygen, different oxidizers are probably of greater importance in determining main fuel dilution and charge stability than burning rate. Thus, substitution of potassium nitrate or potassium perchlorate for sodium nitrate would have a beneficial effect on moisture uptake during storage. On the other hand, variation in the content of a given oxidizer is one of the strongest and most practical means of influencing burning rate. Table 16.3-1 indicates the extent of the control available in a 6-inch annular-charge system in which other flow and burner variables have been held constant [40].

Mixtures with slightly higher concentration (15 per cent) of nitrate are capable of self-sustained combustion in the absence of air and form the basis of the flare-type charge with burning rates of 20 in/min, and in certain Bureau of Mines formulations, as high as 180 in/min [11]. A third form of combustion intermediate between the annular and flare type has been observed with low nitrate concentrations, particularly with aluminum. Labeled "fizz burning", an annular charge is ignited at its downstream face and "cigarette burns" in the upstream direction. The recirculation zone at the bluff burning face plays a stabilizing role similar to that in the ordinary

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

TABLE 16.3-1

Linear Burning Rate in Magnesium Charges as a Function of $NaNO_3$ Content

(2% Linseed oil, ϕ = 1)

Per Cent $NaNO_3$	V_1, in /min
0	(2.4)*
2.5	2.8
5.0	3.7
7.5	5.1
10.0	7.3
12.5	12.0

* Extrapolated

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C. SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

baffle-type flame holder. Though relatively unexplored, linear burning rates as low as 1 in/min appear possible under altitude conditions with this technique. Since large fuel flows are not required for high-altitude operation, the way may be opened for achieving the long burning periods (>30 minutes) required for intercontinental flight.

With some oxidizers, particle size appears to be a rate-controlling factor. In a 7.5 per cent sodium nitrate annular charge the burning rate increased linearly by 75 per cent when the mesh size of the nitrate was decreased from -40 +70 to -140 +200.

Changing the type and concentration of binder serves a better purpose when employed to tailor the physical properties of the charge. Thus, substituting rubber cement for linseed oil [41] raises the compressive strength of a magnesium charge by a factor of 6. Ordinarily, the linseed-oil charges crush at roughly 1200 lbs/in^2. Since one of the principal difficulties with boron charges is their poor structural properties, this type of substitution can be very important. Of less practical use is the 60 per cent decrease in burning rate when the linseed-oil content of a magnesium-ammonium dichromate charge is raised from 1 to 5 per cent.

Little leeway is available for controlling the burning rate of annular charges by changing their density, because of the overriding need for high structural strength. The technique may, however, become useful in adjusting the burning rate of the mechanically supported flare-type charge. For example, the rate of a Mg-15% sodium nitrate flare can be increased from 20 in/min at a specific gravity of 1.25 to 45 in/min by molding at a sufficiently lower pressure to obtain a specific gravity of 0.75.

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

Equivalence ratio and initial charge temperature were included, perhaps somewhat arbitrarily, in the list of burner-design variables which could be employed to establish control over burning rate. Only a brief discussion of their effects is warranted, since there is little here of utility to the designer. The burning rate is almost constant with equivalence ratio, decreasing no more than 5 per cent as an initial equivalence ratio of 0.5 is enriched to 1.5 in the lower nitrate charges (approximately 5 per cent sodium nitrate). The effect is somewhat greater at higher nitrate concentrations but still amounts to no more than a 10 per cent decrease over the same range in 10 per cent sodium nitrate compositions. The temperature effect is similarly small. Lowering the charge to -80°F resulted in a 10 per cent decrease in air specific impulse in the 190-200 range [40], and it is probable that only a part of this loss can be ascribed to a lowered burning rate.

The third item in this group, i.e., the observation that the linear burning rate of the annular charges is a strong function of the air mass flow through the central passage, is one of great significance. The magnitude of the effect is illustrated in Fig. 16.3-4. An eightfold decrease in air mass flow per unit cross-sectional area produces a roughly threefold decrease in burning rate. In brief, the solid fuel ramjet has a self-metering characteristic which at least partly compensates for the otherwise large changes in air-fuel ratio that would be expected as the ramjet operated across broad ranges of speed and altitude. Since the data points in Fig. 16.3-4 were obtained by both varying the mass flow at constant inlet pressure through the use of nozzles and by lowering both pressure and mass flow in an altitude test stand, it is believed that the parameter selected for the abscissa is sufficiently definitive for design purposes. Intensive study may, however, reveal that a more

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS TITLE 18, U.S.C. SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

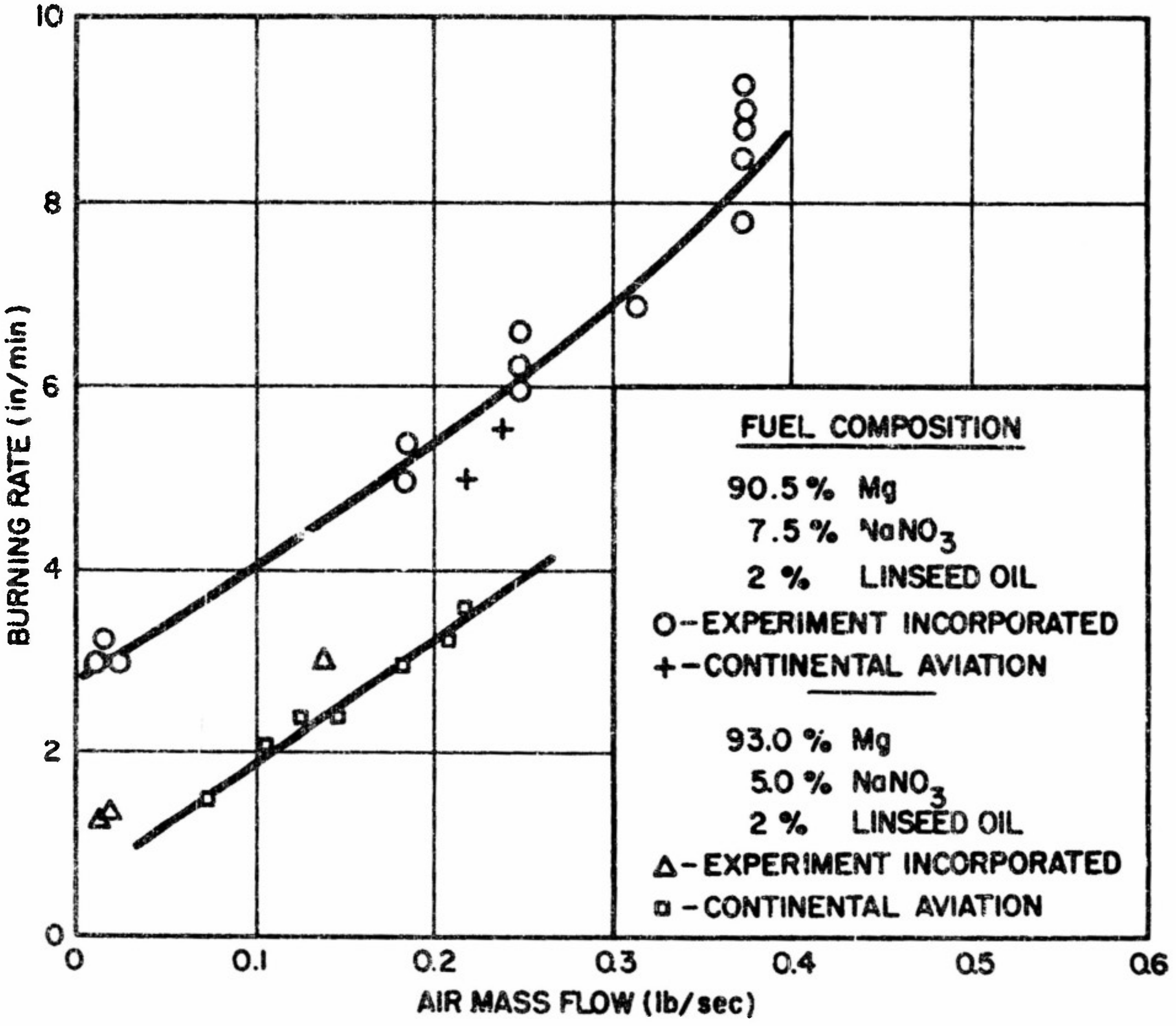


Fig. 16.3-4 LINEAR BURNING RATE OF ANNULAR CHARGES AS A FUNCTION OF AIR MASS FLOW

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C. SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

general expression in terms of separate pressure and velocity functions can be written. For example, static tests on flare-type charges have shown that the burning rate decreases with lowered pressures [11].

Thrust Control

Since the primary objective of controlling the burning rate is the subsequent control of the thrust output of the engine, it is desirable to broaden the discussion in the latter terms. There are two connotations to the phase "thrust control". The first implies reproducibility, and the problem is little different from that encountered in solid-propellant rockets. The data listed in Table 16.3-2 indicate that even when no extraordinary quality-control procedures were employed in the formulation stages, reasonable reproducibility was obtained. The second implication is one of variable thrust to meet varying flight conditions. Several methods for meeting this requirement in solid fuel ramjets will be outlined in the following paragraphs.

The simplest and most direct approach is to take advantage of the self-metering characteristic just discussed. Consider a 6-inch diameter missile of the form sketched in Fig. 16.3-1(a). Table 16.3-3(a) summarizes the performance expected over the flight Mach number range of 1.2 to 2.4 at sea level. It is apparent that a constant air specific impulse condition can be established and that the net thrust relationship above Mach 1.6 is at least compatible with a uniformly accelerating trajectory. A free-jet test at Mach 1.6 checked these results insofar as a burning time of 12 seconds and a minimum air specific impulse of 184 were obtained. Table 16.3-3(b)

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C. SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

TABLE 16.3-2

Thrust Reproducibility in Magnesium Burners

Run No.	Charge Type	m_a	ϕ	Burn Time	S_a	Lbs Thrust
167	2-in Annular	0.66	0.74	3.5 sec	172	
168	"	"	0.81	3.3	170	
170	"	"	0.64	3.8	175	
171	"	"	0.74	3.5	172	
175	"	0.44	0.81	4.8	172	
176	"	"	0.74	5.0	167	
177	"	"	0.76	5.0	170	
74	2-in Split Flow	22*	0.35	4.0	146	
75	"	"	0.35	4.1	148	
82	"	"	0.34	4.4	148	
85	"	"	0.24	5.6	126	
86	"	"	0.24	5.6	126	
68	"	16*	0.37	5.2	139	
89	"	"	0.38	5.9	145	
67	"	"	0.39	5.0	144	
69	"	"	0.41	5.4	150	
76	"	10*	0.24	6.6	124	
77	"	"	0.24	6.6	120	
78	"	"	0.23	6.9	114	
9	6-in Split Flow**			13.5		330
10	"			13.0		330
12	"			13.5		320
20	"			13.5		310
24	"			13.5		320
25	"			14.0		320

* % total m_a thru center of charge

** Free-jet tests ($M_o = 1.57$; $\frac{A_2}{A_o} = 3.0$)

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

TABLE 16.3-3(a)

Constancy of Impulse at Sea Level over Velocity Range

Flight Mach No.	Burning Time, Sec	ϕ	S_a	C_T	C_D	Net Thrust Lbs
1.2	18.8	0.85	189	0.44		
1.4	15.0	0.82	188	0.53		
1.6	11.1	0.80	187	0.62	0.29	250
1.8	9.8	0.81	188	0.56	0.27	275
2.0	8.2	0.86	190	0.51	0.25	300
2.2	7.4	0.88	191	0.45	0.24	295
2.4	6.4	1.04	193	0.40	0.23	285

TABLE 16.3-3(b)

Constancy of Impulse at M_o = 1.8 over Altitude Range

Altitude Ft x 10^3	Burning Time, Sec	ϕ	S_a	C_T	C_D	Net Thrust Lbs
0	9.8	0.81	188	0.56	0.27	275
5	12.5	0.75	186	0.57	0.27	235
15	14.8	0.85	189	0.65	0.27	200
25	22.4	0.87	190	0.73	0.28	160
35	30.4	0.91	192	0.82	0.29	120
45	40.0	1.10	195	0.85	0.30	75

Estimated performance of missile calculated on basis of:

1. Diffuser ratio = 4:1
2. Burner drag coefficient = 6
3. Diffuser efficiency = 60%
4. No tail constriction
5. Burning rates from experimental results at Continental Aviation and Experiment Incorporated (Fig. 16.3-4)
6. The S_a for various air-fuel ratios was taken from data obtained in 6-inch burner by Continental Aviation
7. Fuel weight = 22 pounds
8. Size of charge = 4 in I.D. x 6 in O.D. x 30 in long
9. Fuel composition = 93% Mg , 5% $NaNO_3$, 2% linseed oil
10. Shock on rim at M_o = 1.6, spilling below, swallowed above.

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C. SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

extends the performance calculations to level flight at a series of altitudes. Again, in spite of the fact that the air mass flow has suffered an eightfold change between sea level and 45,000 feet, the air specific impulse is surprisingly constant.

The foregoing basic technique can be given greater flexibility and made subject to more precise control by going to the split-flow type of design [Fig. 16.3-1(b)]. The insertion of a flow metering orifice at the downstream end of the canister eliminates the trend to an increasing S_a as the burning surface becomes larger toward the end of the run. A comparison of the two thrust-time curves in Fig. 16.3-5 illustrates the effectiveness of this device. Performance predictability is further enhanced by the maintenance of a constant internal drag. In practice mild steel orifices have held up quite well in magnesium burners, but graphite or ceramic orifices are required for aluminum. Proper selection of the area ratio of the internal and external air passages is, of course, important. The main goal is to have the central flow reduced or raised automatically, depending upon whether the temperature produced therein increases or decreases because of altered inlet conditions in flight. This aerothermodynamic "choking" control is in the same direction as, and supplements, the inherent self-metering characteristic of the charge.

A still further refinement would be the installation of a valve arrangement (e.g., a butterfly or rotating sleeve in the extension to the inlet of the central duct). The position of the valve would be coordinated with the momentary thrust demand imposed on the engine throughout its flight and maneuvering path.

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C. SECTIONS 793 AND 794. THE [illegible]

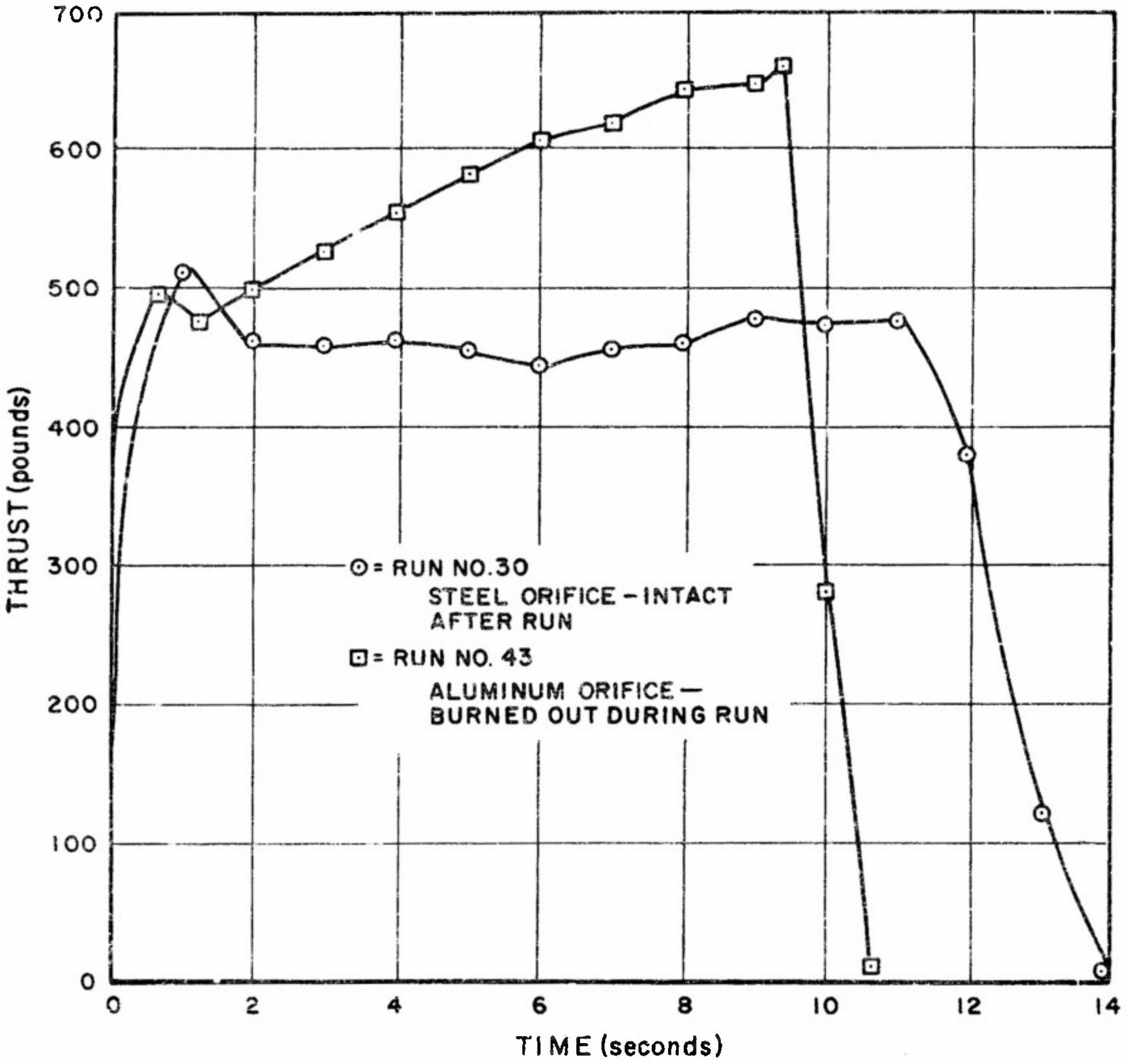


Fig. 16.3-5 EFFECT OF METERING ORIFICE AT DOWNSTREAM END OF FUEL CHARGE ON THRUST FROM SIX-INCH SPLIT-FLOW BURNER

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

No attempt will be made to detail the many other possibilities for thrust control. Their number is limited only by the ingenuity of the designer. For the purpose of suggestion, several approaches can be listed.

1. Combinations of flare and annular charges.
2. Multiple charges of one or both types sequentially fired.
3. Formulation of charges. Entire charge can be altered, or longitudinal and radial variations can be introduced in a programmed manner.
4. Missile can be overpowered and servo-activated drag spoilers added.
5. Controlled diffuser bleeds.
6. Variable-area intakes and exhausts, including combustible arrangements fabricated from the fuel composition.

Burner Efficiency

In Fig. 16.3-6 the experimental air specific impulse obtained under sea-level and altitude conditions with both flare and annular magnesium charges is plotted as a function of equivalence ratio. A 2-inch diameter burner was employed in most of the runs, the only exception being a 4-inch unit in the altitude runs with annular charges. The theoretical air specific impulse-equivalence ratio curve for magnesium is included. Employing the ratio of observed to theoretical S_a as a measure of impulse efficiency, it is seen that all of the points are above the 80 per cent level and the majority above 85 per cent. These

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

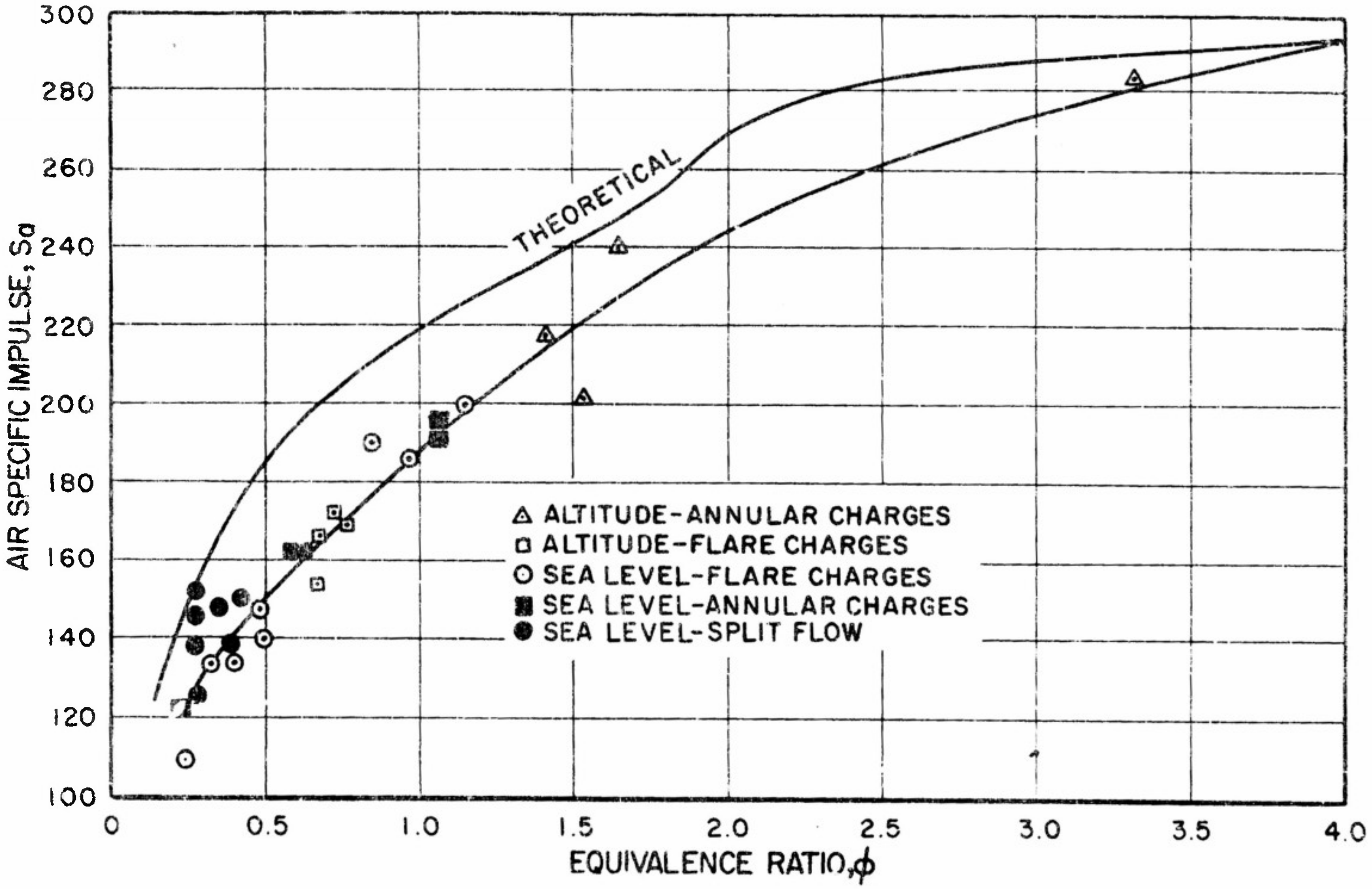


Fig. 16.3-6 AIR SPECIFIC IMPULSE vs EQUIVALENCE RATIO FOR MAGNESIUM FUEL

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

percentages may be slightly inaccurate, since absence of thermodynamic data for sodium oxide prevented exact determination of the effect of the sodium nitrate in development of the theoretical S_a curve. Also, the data have not been corrected for heat losses to the chamber walls. Of particular interest is the fact that the impulse efficiency seems to suffer but little from the lowered pressure conditions of the altitude runs. This is more clearly shown in Fig. 16.3-7 where the impulse efficiency is plotted as a function of combustion-chamber inlet pressure. For comparison, a typical performance curve for a 2-inch burner operating on a homogeneous vapor-phase hydrocarbon fuel is given [26].

Further impulse-efficiency data are given in Table 16.3-4. The first five runs show that the 2-inch annular magnesium burner appears to reach maximum efficiency in a 24-inch tailpipe. Excessive heat losses to the walls probably account for the lower efficiencies with the very long chambers. The S_a values have not been corrected for these losses which, by direct measurement, amounted to 23 per cent and 12 per cent respectively in runs 236 and 225. Under similar conditions with hydrocarbon burners where the heat loss is about 5 per cent, an efficiency of 85 per cent is obtained with a 14-inch tailpipe [27].

The next eight runs indicate the generally more efficient operation observed in the split-flow annular type of system. The heat losses through the wall appear to be small, and the downstream mixing processes are enhanced by this technique. Here the initial combustion within the core of the charge is quite rich ($\phi = 1.5$ to 4). The resulting heat release is, however, still sufficient to vaporize magnesium. The secondary and principal combustion thus occurs under the favorable condition of rapid turbulent admixture of two gaseous streams. The

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C. SECTIONS 793 AND 794. THE TRANSMISSION OR

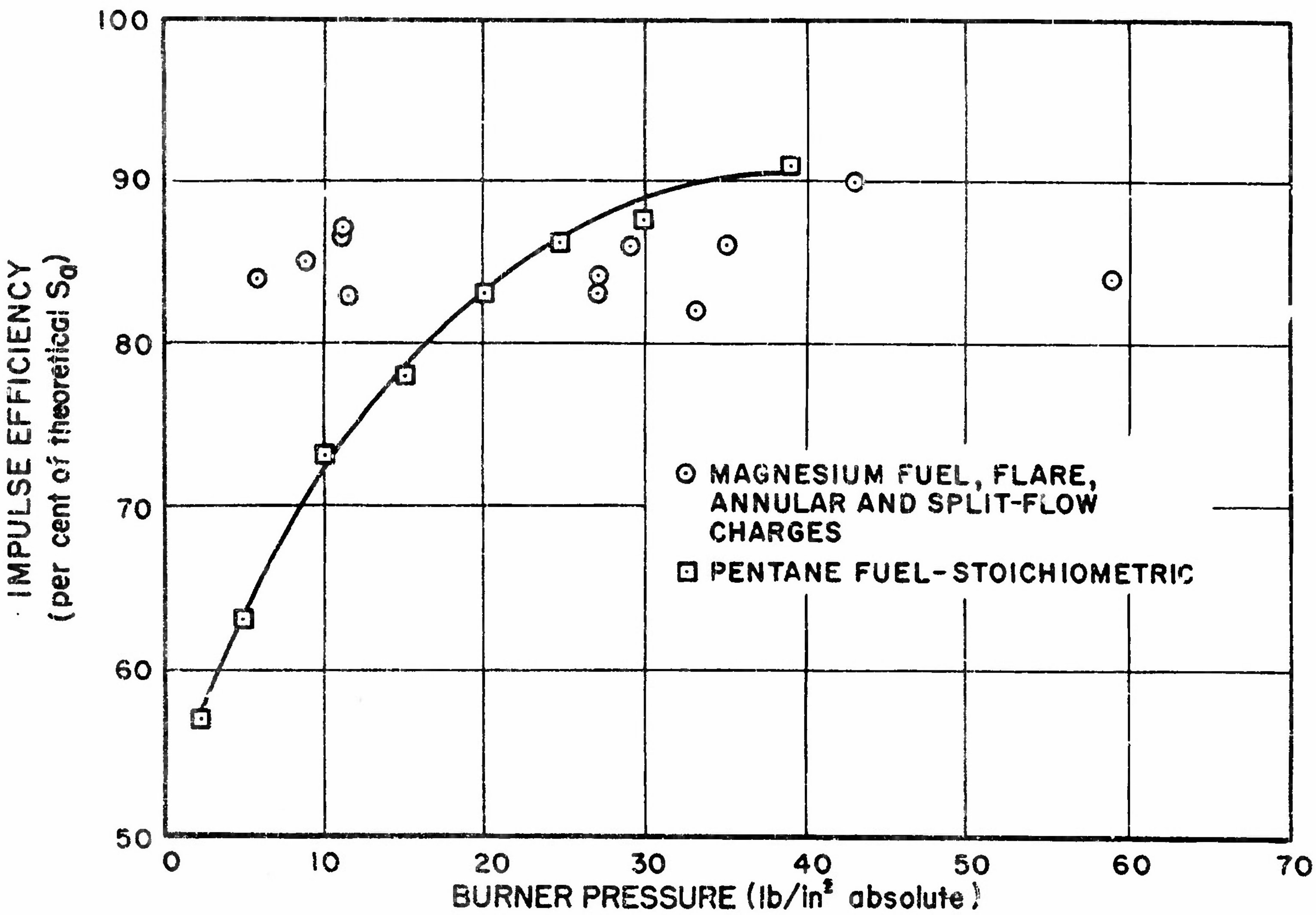


Fig. 16.3-7 EFFECT OF PRESSURE ON BURNING EFFICIENCY

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS TITLE 18, U.S.C. SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

TABLE 16.3-4

Impulse Efficiency in Magnesium Burners

Run	Charge Type	Tailpipe (inches)	ϕ	S_f	S^*_a	S_a/S_a(theo)	I_{sp}
192	2-in. Annular	96	0.75	555	163	80	
236	"	74	0.65	650	165	83	
225	"	24	0.65	665	168	85	
242	"	12	0.60	575	135	70	
240	"	4	0.55	530	114	60	
59	2-in Split Flow	30	0.27	1390	149	97	
60	"	30	"	1370	149	97	
61	"	21	"	1410	151	99	
62	"	21	"	1325	147	96	
63	"	12	"	1350	138	90	
64	"	12	"	1340	138	90	
66	"	7.5	"	1210	128	84	
65	"	7.5	"	1170	124	81	
45**	6-in Split Flow	40	0.33	1160	143	88	410
30**	" (Mixer)	40	0.35	1150	153	92	460
31**	" (Mixer)	40	0.35	1165	154	93	475

* Uncorrected for heat loss to walls

** Free jet; $M_o = 1.83$, $A_2/A_o = 3.0$

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW.

split-flow system also allows improved fuel economy. Thus, the same performance outlined in Table 16.3-3(a) for a 6-inch missile at an S_a of 190 can be obtained at 140 by adjusting the inlet area for higher air mass flows. This, of course, cannot be done with the simple annular charge, since then the effect of a greater mass air flow is merely to increase the burning rate and hence the S_a

The next three runs reveal that further gains can be found in the judicious use of mixing devices. The 6-inch diameter split-flow charge gave an impulse efficiency of 88 per cent under Mach 1.83 conditions in a free-jet test. A small perforated "can" mixer (see Chapter 9) attached to the downstream end of the charge increased this figure to between 92 and 93 per cent. No intensive effort was made to optimize the mixing system. These impulse efficiencies correspond to combustion efficiencies (based on equivalence ratios) of the order of 80 per cent.

The highly doped aluminum and boron charges described in an earlier section burned with impulse efficiencies of approximately 90 and 80 per cent respectively, the theoretical S_a in each instance being based on the actual formulation used.

Combustion Limits

As ordinarily used, "combustion limits" have little meaning in systems where the "diffusion" of atmospheric oxygen to a solid surface is an important preliminary to subsequent reaction. That is, the range of stable burning is extraordinarily broad. The runs in Fig. 16.3-6 lie between equivalence ratios of 0.25 and 3.3. These are not true limits, however, but merely the change extent of the investigations. Thus, in the split-flow burners the combustion within the charge is often carried out at equivalence ratios in excess of 4.

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

NOMENCLATURE

Symbol	Definition	Units
ϕ	equivalence ratio	
S_a	air specific impulse	lb-sec/lb
S'_f	fuel specific impulse	lb-sec/lb
S_{af}	air-fuel specific impulse	lb-sec/lb
m_f	fuel flow rate	lbs/sec
m_a	air flow rate	lbs/sec
V_l	linear burning rate	in/min
S	total area of burning surface	in^2
γ	ratio of specific heats	
d	fuel density	lbs/ft^3

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C. SECTIONS 793 AND 794. THE TRANSMISSION OR

APPENDIX

THEORETICAL AIR SPECIFIC IMPULSE, FUEL SPECIFIC IMPULSE, FLAME TEMPERATURE, AND EXHAUST COMPOSITION FOR SEVERAL SOLID FUEL SYSTEMS

In making the impulse calculations the usual relations were employed, i.e.,

$$S_{af} = \sqrt{\frac{2(\gamma + 1)\ RT}{\gamma g m}} ,$$

$$S_a = S_{af}\ (1 + \frac{m_f}{m_a}) ,$$

$$S_f = S_{af}\ (1 + \frac{m_a}{m_f}) .$$

If the exhaust stagnation temperature is in degrees Kelvin, R becomes 2776 ft-lbs/°K/lb mol. The acceleration due to gravity, g, is 32 ft/sec^2 and the air and fuel mass flows, m_a and m_f, are in lbs/sec. The presence of the solid (or liquid) phase in the exhaust was allowed for in the manner suggested by Maxwell, Dickinson, and Caldin [Aircraft Engineering, XXIII, 212, (1946)]. The term, m, which is the average molecular weight for a gaseous exhaust, is now taken as the weight of exhaust gases plus the weight of exahust solids divided by the mols of exhaust gases only. The specific heat ratio, γ, is computed as the C_p for the exhaust gases plus the C_p of the exhaust solids divided by the C_v for the exhaust gases plus the C_p for the exhaust solids. Temperature and velocity equilibrium between exhaust gases and exhaust solids are assumed. That this procedure leads to no

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE [illegible] U.S.C. SECTIONS 793 AND 794. THE TRANSMISSION OR [illegible] PROHIBITED BY LAW

inaccuracies in excess of 5 per cent in the range of solid-gas ratios considered was demonstrated by direct experimental investigation (Reference 47 in text). The thermodynamic data employed are indicated in footnotes to Tables 16A-1, 16A-2, 16A-3, and 16A-4. Many of these data are questionable so that the values for the theoretical performances of magnesium, aluminum, boron, and decaborane should be employed only in realization of this fact. It was assumed that no heat was available from phase changes (condensation and crystallization) during the passage of the stream from the combustion chamber through the exit section. The accuracy of this assumption is difficult to determine, but at least it leads to conservative theoretical performance figures. In the case of magnesium at the stoichiometric ratio, if the heats of fusion and evaporation are available, the S_a is 242, but if unavailable, this is lowered to 220.

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

TABLE 16A-1

Theoretical Performance of Magnesium at Various Equivalence Ratios

(P = 3 atm. $T_o = 298^{o}K$)

	Exhaust Composition Mols/Mol Exhaust								O	Flame Temp. (°K)	Mol Wt Exhaust	γ	lb air / lb fuel	S_a	S_f
ø	MgO Solid	MgO Liquid	MgO Vapor	Mg Vapor	N_2	O_2	N	NO							
0.15	0.0611				0.766	0.173				1430	31.4	1.278	19.1	124	2360
0.25	0.100				0.750	0.150				2046	33.1	1.245	11.4	150	1710
0.50	0.167		0.022		0.697	0.074		0.029	0.011	2943	36.6	1.203	5.7	187	1070
0.75		0.195	0.075		0.667	0.028		0.022	0.013	3175	38.9	1.193	3.82	204	780
1.0		0.136	0.151		0.650		0.003			3360	39.9	1.192	2.85	220	630
1.5		0.230	0.066	0.148	0.556					3160	40.3	1.186	1.91	241	460
2.0	0.221		0.037	0.258	0.484					3045	38.6	1.132	1.43	269	384
4.0	0.170			0.512	0.318					1390	28	1.230	0.715	294	220

THERMAL PROPERTIES OF MgO USED IN CALCULATION OF THE ABOVE VALUES:

Heat capacity of liquid and solid cal/°K/mol = $10.86 + 1.2 \times 10^{-3}T - \frac{209 \times 10^{3}}{T^{2}}$

Melting point = 3073°K; Heat of fusion 18,500 cal /mol

Vapor pressure = $\ln P = 19.25 - \frac{45,100}{T}$; heat of vaporization 90,000 cal /mol

Heat of formation = 146,100 cal /mol

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

TABLE 16A-2

Theoretical Performance of Aluminum at Various Equivalence Ratios

(P = 3 atm. $T_o = 298^oK$)

	Exhaust Composition - Mols/Mol Exhaust						Flame Temperature (°K)	Mol Wt Exhaust	γ	lb air / lb fuel	S_a	S_f
	Al_2O_3			Al Vapor	N_2	O_2						
ø	Solid	Liquid	Vapor									
0.10	0.0141				0.795	0.191	1010	30.25	1.315	38.2	103	3940
0.25	0.0356				0.804	0.160	1870	32.35	1.253	15.3	143	2185
0.50		0.0614	0.0112		0.818	0.109	2735	36.05	1.203	7.64	175	1335
1.0			0.151		0.849		3200	39.15	1.217	3.84	202	770
1.5		0.0723	0.0587	0.131	0.738		3000	40.5	1.186	2.54	214	540
2		0.109		0.220	0.670		2665	41.1	1.171	1.91	220	420

THERMAL PROPERTIES OF Al_2O_3 USED IN THE ABOVE CALCULATIONS:

Heat capacity of solid and liquid cal/°K/mol = $22.08 + 9.00 \times 10^{-3}T - \frac{520 \times 10^3}{T^2}$

Melting point = 2318°K; Heat of fusion 26,000 cal /mol

Vapor pressure = $\ln P = 24.20 - \frac{57,500}{T}$; Heat of vaporization 115,000 cal /mol

Heat of formation = 380,000 cal /mol

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS TITLE 18, U.S.C. SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

TABLE 16A-3

Theoretical Performance of Boron at Various Equivalence Ratios

(P = 3 atm. T_o = 298°K)

Exhaust Composition - Mols/Mol Exhaust							Flame Temp. (°K)	Mol Wt Exhaust	γ	lb air / lb fuel	S_a	S_f
	B_2O_3		Boron		N_2	O_2						
ø	Liquid	Vapor	Solid	Vapor								
0.25	0.0356				0.804	0.160	1430	31.4	1.269	38.2	121	4630
0.50		0.0726			0.818	0.109	2000	31.4	1.250	19.1	148	2820
1.00		0.151			0.849		3110	34.3	1.210	9.55	187	1785
1.50		0.131	0.092	0.039	0.738		2450	34.4	1.196	6.35	173	1100

Thermal properties of B_2O_3 used in above calculations were taken from tables and charts in Technical Report to Bureau of Aeronautics, Navy Department, from Heat and Power Division, National Bureau of Standards, Washington, D. C. on "Thermal Properties of Gaseous Equilibria of Boron, Oxygen and Oxides of Boron" by Paul E. Wacker, Harold W. Woolley and Myron F. Fair, January 25, 1945.

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS TITLE 18, U.S.C. SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

TABLE 16A-4

Theoretical Performance of Decaborane at Various Equivalence Ratios

(P = 3 atm. T_o = 298°K)

Exhaust Composition - Mols/Mol Exhaust												Flame Temp. °K	Mol Wt Exhaust	γ	lb air per lb fuel	S_a	H_r
φ	B_2O_3(g)	B_2O_3(l)	H_2O	O_2	N_2	H_2	OH	H	O	NO	B						
0.25	-	.0237	.0332	.157	.787	-	-	-	-	.000670	-	1485	30.08	1.285	49.44	126	6210
0.50	.0171	.0131	.0650	.105	.785	-	.00230	-	.000500	.0110	-	2199	29.55	1.264	24.72	158	3902
0.75	.0172	-	.0945	.0429	.771	.00163	.00642	.00590	.00186	.0107	-	2490	30.27	1.239	16.44	170	3771
1.00	.0920	-	.100	.00685	.755	.0179	.0107	.00680	.00335	.00720	-	2827	30.29	1.228	12.36	185	2284
1.33	.123	-	.0324	-	.704	.115	.00182	.0230	.00025	000470		2905	29.24	1.223	9.29	193	1813
2.5	.0962	-	-	-	.543	.230	-	-	-	-	.132	2545	27.40	1.225	4.94	205	1014
3.0	.0863	-	-	-	.486	.247	-	-	-	-	.180	2394	26.94	1.267	4.12	206	848
4.0	.0557	.0162	-	-	.403	.275	-	-	-	-	.248	2294	26.85	1.285	3.09	215	685
5.0	.0310	.0306	-	-	.348	.294	-	-	-	-	.287	2232	26.51	1.298	2.47	225	557
7.5	.00415	.0418	-	-	.256	.325	-	-	-	-	.374	2015	25.74	1.326	1.65	248	409
10.0	.0004	.0355	-	-	.203	.343	-	-	-	-	.418	1802	24.53	1.338	1.24	262	333

Wherever possible, National Bureau of Standards tables [1] were used to obtain thermodynamic data for the products considered. Enthalpy tables compiled by Huff and Gordon [2] were employed for liquid and gaseous B_2O_3 and for solid boron. The heat of formation of decaborane was taken as 8.00 Kcal/mol [3]. The heat of formation of gaseous B_2O_3 was taken as -223.162 Kcal/mol [4] and of liquid B_2O_3 as -339.8 Kcal/mol [5]. This gives a heat of vaporization of 116.6 Kcal/mol while Speiser, Naiditch, and Johnston [6] give a value of 77.6 Kcal/mol. Vapor pressure data, used to determine the equilibrium between gaseous B_2O_3 and liquid B_2O_3 were taken from Speiser, Naiditch, and Johnston [6].

1. "Selected Values of Chemical Thermodynamic Properties," National Bureau of Standards, Vol. I, Series III.
2. Huff and Gordon, "Tables of Thermodynamic Functions for Analysis of Aircraft-Propulsion Systems," NACA TN 2161.
3. "Selected Values of Chemical Thermodynamic Properties," National Bureau of Standards, Vol. I, Series I.
4. "Physical Properties and Thermodynamic Functions of Fuels, Oxidizers and Products of Combustion, III," Battelle Memorial Institute, Project Rand Report, R-196, September 1 (1949).
5. Kubaschewski and Evans, "Metallurgical Thermochemistry," Academic Press, Inc., New York (1951).
6. Speiser, Naiditch, and Johnston, "The Vapor Pressure of Inorganic Substances - B_2O_3," J. Am. Chem. Soc., 72, 2578 (1950).

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

REFERENCES

1. Alperin, M., Theoretical Calculations of the Thrust of a Solid Fuel Ramjet, Jet Propulsion Laboratory, California Institute of Technology, Progress Report No. 3-20, 1947.

2. Anderson, R. C., Preliminary Studies on Suspensions of Solids as Fuels for Ramjet Propulsion (Restricted), Defense Research Laboratory, The University of Texas; Applied Physics Laboratory, The Johns Hopkins University, CM-789, 1946.

3. Anon., Interim Progress Report of Meteor Project (Confidential), Massachusetts Institute of Technology, Meteor Report No. 49, 1950.

4. Anon., Interim Progress Report of Meteor Project (Confidential), Massachusetts Institute of Technology, Meteor Report No. 55, 1950.

5. Baker, W. T., Davis, T., and Matthews, S. E., Reduction of Drag of a Projectile in a Supersonic Stream by the Combustion of Hydrogen in the Turbulent Wake (Confidential), Applied Physics Laboratory, The Johns Hopkins University, CM-673, 1951.

6. Barr, W. J., Fenn, J. B., and Mullen, J. W. II, Suggested Applications for Recently Developed Solid Fuel Ramjet Systems (Confidential), Experiment Incorporated, Memo No. 197, 1950.

7. Bartel, H. R. and Rannie, W. D., Solid Fuel Combustion as Applied to Ramjets (Restricted), Jet Propulsion Laboratory, California Institute of Technology, Progress Report No. 3-12, 1946.

8. Berl, W. G., Bumblebee Survey Report No. 40 (Confidential), July 1946 and Bumblebee Survey Report No. 49 (Confidential), December 1946.

9. Bowling, A. G., Use of Sweat Cooling to Prevent Build-up of Oxide in a Combustion Chamber (Restricted), Royal Aircraft Establishment, England, Tech Note Aero. 1978, S. D. 86, 1948.

10. Branstetter, J. R., Lord, A. M., and Gerstein, M., Combustion Properties of Aluminum as Ramjet Fuel (Confidential), NACA RM E51B02, 1949.

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

11. Damon, G. H. and Herickes, J. A., Combustion of Solid Fuels for Ramjets, Bureau of Mines Progress Report Nos. 3-23 on Navy Department, Bureau of Ordnance Project, (No. 3 Confidential, Nos. 4-17 Restricted, Nos. 18-23 Confidential), October 1946 to December 1951.

12. Davis, H. and Hottel, H. C., Combustion Rate of Carbon, Ind. Eng. Chem., 26, 889, (1934).

13. Faget, M. A. and group from NACA, visit to Experiment Incorporated April 6, 1951.

14. Fennell, T.R.F.W., The Approximate Analysis of Aluminum Fuel Combustion Products, Royal Aircraft Establishment, England, Tech. Note Chem. 1087, 1949.

15. Gammon, B. 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 (Confidential), NACA RM E5_C12, 1951.

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

17. Gammon, B. 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 (Confidential), NACA RM E51D25, 1951.

18. Gammon, B. E., Preliminary Evaluation of the Air and Fuel Specific-Impulse Characteristics of Several Potential Ram-Jet Fuels, IV: Hydrogen, α-Methylnaphthalene, and Carbon (Confidential), NACA RM E51F05, 1951.

19. Gibbs, J. B. and Cook, P. N., Jr., Preparation and Physical Properties of Metal Slurry Fuels (Confidential), NACA RM E52A23, 1952.

20. Lippisch, A. M., History of the Origin of Project LI-P 13 (Athodyd), Issued by U. S. Navy Bureau of Aeronautics, Technical Intelligence Liaison Unit, BAGR-DC, Wright Field, Dayton, Ohio.

21. Longwell, J. P., (private communication).

22. Lorin, R., L'Aerophile, 229, (1913).

23. Lorin, R., L'Aerophile, 513, (1913).

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

24. Mazurkiewicz, E. J., Booster Ramjet Study (Confidential), Continental Aviation and Engineering Corporation, Report No. 375, 1948.

25. Mazurkiewicz, A. G., Some Rheological Properties of Aluminum Suspensions in Kerosene, Royal Aircraft Establishment, England, Tech. Note Chem. 1055, 1948.

26. Mullen, J. W., II and Fenn, J. B., Burners for Supersonic Ramjets. Some Factors Influencing Performance at High Altitudes - A Resume (Confidential), Experiment Incorporated, TM-188; Applied Physics Laboratory, The Johns Hopkins University, CF-1383, 1950.

27. Mullen, J. W., II, Fenn, J. B., and Garmon, R. C., Ind. Eng. Chem., <u>43</u>, 195, (1951).

28. Olson, W. T. and Gibbons, L. C., Status of Combustion Research on high-Energy Fuels for Ramjets (Confidential), NACA RM E51D23, 1951.

29. Parker, A. S. and Hottel, H. C., Ind. Eng. Chem., <u>28</u>, 1334, (1936).

30. Parker, W. G. and Wolfhard, H. G., Temperature Measurements of Flames Containing Incandescent Particles, Proc. Phys. Soc., <u>62</u>, Series B, (1949).

31. Pomeroy, A. L., Thompson Products, Inc. private communications, February 1951.

32. Resume of visit to Wallop's Island, Experiment Incorporated Internal Memo, May 1, 1951.

33. Roberson, E. C., Thrust and Fuel Economy Characteristics of Potential Ramjet Fuels (Restricted), National Gas Turbine Establishment, England, Report No. R.17, 1947.

34. Sanford, E. S., Magnesium Fueled Ramjet Booster for Triton, Applied Physics Laboratory Internal Memo to J. H. Walker, October 23, 1951.

35. Sanford, E. S., Solid Fuel Ramjet Midcourse Sustainers for Terrier, Applied Physics Laboratory Internal Memo to J. H. Walker, December 13, 1951.

36. Saenger, E. and Bredt, I., Ueber einen Lorinantrieb fuer Strahljaeger, <u>Berlin-Adlershof</u>, <u>Deutsche Forschungsanstalt fuer Segelflug E. V.</u>, October 1943, (Available as A.M.C. translation No. F-TS-901-RE), 1947.

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

37. Schwabl, H., Systematische Versuche uber die Verwendung von Festkraftstoffen in Lorin - Triebwerken, Wien, Luftfahrtforschung, January 1945. (Available as A.M.C. translation No. F-TS-1021-RE.)

38. Scott, R. C., Bailey, M., Burke, J. A., Moomaw, C. E., and Wolf, R. L., Solid Fuel Ramjets III. Final Flight Test Report of Six PTV-N-4e (MTV-Mk 1-Mod 3) Magnesium-Fueled Test Vehicles (Confidential), Experiment Incorporated; Applied Physics Laboratory, The Johns Hopkins University, CM-727, 1952.

39. Smith, F. W., Predicted Combustion Characteristics of Brush Carbon Spheres in High-Velocity Air, Massachusetts Institute of Technology, Meteor Report No. 6, 1947.

40. Squiers, J. C. and Collins, W., Solid Fuel Ramjet Development (Confidential), Continental Aviation and Engineering Corp. Summary Report on Air Force Contract W-33-038-ac-13371, 1950.

41. Squiers, J. C. and Collins, W., Continental Aviation and Engineering Corp. Progress Report on Contract W-33-038-ac-13371, 1950.

42. Squiers, J. C., Gun-Launched Ramjet Projectile, Continental Aviation Engineering Corp. Progress Report on Army Ordnance Contract DA-20-018-ORD-12270, April 1951 - April 1952.

43. Tower, L. K. and Branstetter, J. R., Combustion Performance Evaluation of Magnesium-Hydrocarbon Slurry Blends in a Simulated Tail-pipe Burner (Confidential), NACA RM E51C26, 1951.

44. Tu, C. M., Davis, H., and Hottel, H C., Combustion Rate of Carbon, Ind. Eng. Chem., 26, 749, (1934).

45. Wascher, W. L., Availability and Cost of High Purity Boron, WADC Memorandum Report, 1952.

46. Wolf, R. L., Solid Fuels for Ramjet Engines, Final Report of Work Done on Purchase Order 40350 for Continental Aviation and Engineering Corp., Experiment Incorporated, TM-229, 1950.

47. Wolf, R. L. and Strode, H. H., Effect of Solid Particles in Ramjet Exhausts, Final Report of Work Done for Air Materiel Command on Contract 12633, Part II, Experiment Incorporated, TM 362, 1951.

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

48. Wolf, R. L., Garmon, R. C., and Bailey, M., Use of Aluminum as a Fuel for Ramjet Engines, Final Report of Work Done for the Reynolds Metals Company, Experiment Incorporated, TM-361, 1951.

49. Wolf, R. L., Garmon, R. C., and Ancarrow, N. H., Progress reports of work done on Contract 12633 S.A. 1(S51-2594), Air Research and Development Command, Wright-Patterson Air Force Base, October to July 1952.

50. Wolf, R. L., Solid Fuel Ramjet Studies, Monthly Progress Reports, February through December 1951 on Contract NOrd 9756.

51. Wolf, R. L. and Curdts, W. T., III, Minutes of the Development Subcommittee Meeting, Bumblebee Propulsion Panel (Confidential), Applied Physics Laboratory, The Johns Hopkins University, TG 63-17, 1951.

52. Wolf, R. L., Scott, R. C., Moomaw, C. E., Bailey, M., and Mullen, J. W., II, Preliminary Report on Recent Flight Tests of a Solid Fuel Ramjet [PTV-N-4e (MTV)] (Confidential), Experiment Incorporated; Applied Physics Laboratory, The Johns Hopkins University, CF-1753, 1952.

53. Wolf, R. L., Bailey, M., Burke, J. A., Moomaw, C. E., and Scott, R. C., Solid-Fuel Ramjets II, Development of Split Flow Combustor System (Confidential), Experiment Incorporated; Applied Physics Laboratory, The Johns Hopkins University, CM-732, 1952.

54. Wolf, R. L., Solid Propellants for Supersonic Ramjets (Confidential), Presented at the Eighth Joint Army, Navy, Air Force Solid Propellant Meeting, Redstone Arsenal, June 6, 1952.

55. Wolf, R. L., Preliminary Calculations on the Use of Solid Fuels in Meteor II, Experiment Incorporated Internal Memos, March 19, 1952 and April 28, 1952.

56. Wolf, R. L., Garmon, R. C., and Longo, A., Combustion of Boron, Quarterly Progress Report on Contract AF 33(038)-12633, Air Research and Development Command, Wright-Patterson Air Force Base, 1953.

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C. SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW

ACKNOWLEDGMENT

The authors wish to acknowledge the efforts of their fellow workers at Experiment Incorporated who at one time or another have contributed to the various solid fuel programs. These include M. Bailey, W. J. Barr, J. A. Burke, Jr., H. F. Calcote, J. B. Fenn, R. C. Garmon, C. E. Moomaw, R. C. Scott, and W. T. Wise.

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C. SECTIONS 793 AND 794. THE TRANSMISSION OR THE REVELATION OF ITS CONTENTS IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW