REGRESSION RATE STUDY FOR A SOLID FUEL RAMJET

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Abstract

An experimental investigation has been carried out to appraise the combustion behaviour of a solid fuel ramjet (SFRJ) under different conditions. Various solid fuels - pure hydrocarbons and fuels with metal additives - have been studied with the aim of increasing the performance of the engine.

All combustion tests were conducted on a connected-pipe stand system, which comprised a large air oxidizer reservoir and a vitiated air heater, so that a wide range of flight Mach numbers and heights could be simulated. The fuel grain is in the shape of a cylindrical shell serving as the combustion chamber, with the ingested air oxidizing the fuel vapour emanating from the chamber walls. To determine the average regression rate of the solid fuel wall, the weight loss method was used by weighing the fuel grain prior to and after each run. The regression rate variation with flight Mach number and altitude on account of changing air mass flux, air inlet temperature and chamber pressure was investigated with a polyethylene (PE) fuel over a wide range. Other hydrocarbon and different metal-laden fuels were also tested under the same test conditions and compared to a hydroxyl terminated polybutadiene (HTPB) fuel, which was chosen as the baseline fuel in this study. Furthermore, some aspects of manufacturing procedures and properties of ramjet fuels are being described.

I. Introduction

For practical application ramjet propulsion systems have gained increased importance. Airbreathing engines have a remarkably higher specific impulse than solid rocket engines in a wide range of flight Mach numbers as shown by different authors[1],[2] (see Fig. 1). Ramjets with subsonic combustion may be potential missile propulsion systems for Mach numbers between 2 and 5. In this group, the SFRJ is of great interest because of its operational simplicity, since it does not require fuel tanks, fuel pumping devices or fuel controls to operate. In spite of the promising advantages, the selection of a solid fuel type requires a relatively complex analysis and many sea-level test firings to study the regression behaviour of the solid fuel under many different combustion configurations.

Fuels for SFRJ propulsion systems have to meet several requirements as well as solid propellants for rockets. Prior to selecting a ramjet fuel, the specific mission has to be considered, because fuel properties like heat of combustion, density, combustion efficiency and regression rate have to be compatible with the mission and determine the flight performance of the missile. Other properties, which are not so closely related to the flight performance, are storability, mechanical properties, signature of exhaust gases, price, etc. Two limiting types of missions,

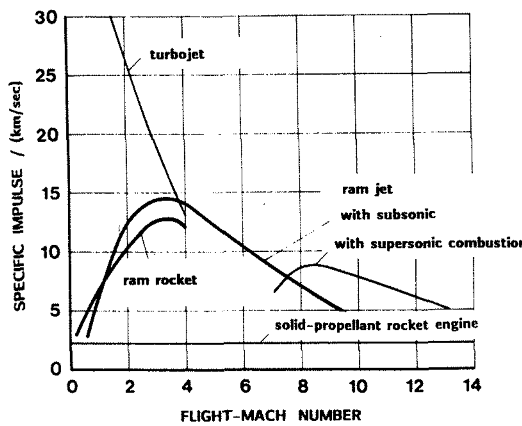

Figure 1. Specific Impulse of Various Propulsion Types

mass-controlled missions and missions which are volume-controlled are generally considered.

The heat of combustion is one of the most important properties of a ramjet fuel. One has to distinguish between the gravimetric and the volumetric heat of combustion, the latter being important for volume-controlled missions. Fig. 2 shows some values for typical fuel candidates. The fuels can roughly be classified into metals, non-metals, half-metals, inorganic compounds and organic compounds. The high potential of some elements like B, Al, Ti and Si is evident. Be and Zr which also have a high potential are not considered in this study. The heats of combustion of organic compounds can be derived from the heats of formation which, in their turn, can be estimated from bond energies or group contributions[3]. The results of such calculations show that, considering solid fuels, the presence of nitrogen or oxygen in the fuel molecule leads to lower gravimetric and volumetric heats of combustion. Thus, the result of these considerations is that ramjet fuels should be hydrocarbons which may be mixed, of course, with suitable metals.

The volumetric heat of combustion is the product of gravimetric heat of combustion and fuel density. Therefore, the fuel density is another important factor that has to be considered in connection with volume-determined missions. The density of hydrocarbon fuels depends on the carbon-to-hydrogen ratio and on the molecular structure. The density increases with increasing carbon-to-hydrogen ratio. Polycyclic structures are most favorable. Several of these high density hydrocarbons have been synthesized in the past, and preparation procedures are given in the literature[4],[5].

The heat of combustion per unit mass of air and the air requirement of the fuel are two parameters of somewhat minor importance but should be mentioned here, too.

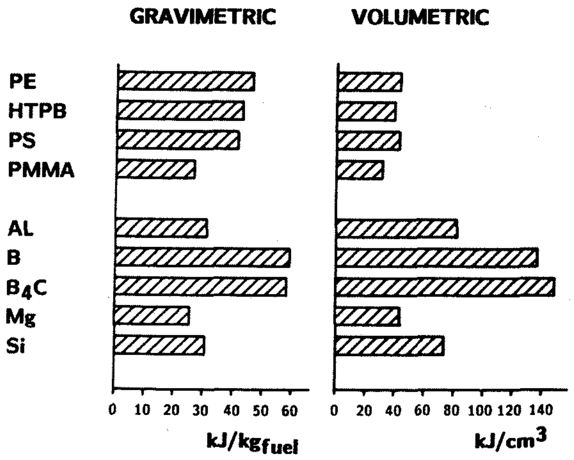

Figure 2. Heating Values of SFRJ Fuel Candidates

The regression rate of a fuel is also an important factor. Regression rate requirements depend on the selected mission. The regression rate is not a fuel property alone, combustor geometry, surface area and heat as well as mass transfer in the combustion chamber are of influence, too. It has been found(6), (7) that the rate of polymer degradation plays an important role in solid fuel ramjet combustion. For instance, the regression rate of HTPB is much higher (about 70 to 80 percent) than that of PE. There are four general mechanisms of thermal decomposition of organic polymers(8): random-chain scission, end-chain scission, chain stripping and cross-linking. Polymers which decompose according to the chain-stripping or cross-linking mechanism are not always suitable for solid fuel ramjet combustion, because they don't burn without residue and tend to char.

Combustion efficiency is another important parameter that has to be considered in solid fuel ramjet combustion. However, combustion efficiency is not a typical fuel property, because it depends mainly on external conditions like residence time, mixing, gas phase reaction rate, combustor geometry, and heat and mass transfer.

Mechanical stability and storability of the ramjet fuel are as important as in connection with solid propellants, but the problems are less complex because the fuel composition is not so complicated. Antioxidants are often added in order to increase the storability.

Ramjet fuels usually do not burn without smoke. This is especially the case with metalized fuels which, of course, cannot be smokeless. Many hydrocarbon fuels produce soot during combustion. Polyethylene is a fuel which has an almost smokeless exhaust.

The price of a ramjet fuel should be low. Therefore, some more exotic high density hydrocarbons might not be suitable. Chemical compounds, which are already produced for other purposes or which are intermediates for other products, are mostly available at low costs as compared to laboratory chemicals. It has also to be considered that the price of an interesting fuel compound being high at present can be considerably lowered if it is produced in very large amounts.

Moreover, ramjet fuels should ignite and burn reliably within the stability limits.

The mechanism of the combustion process and the flow characteristics in SFRJ combustors with non-metalized fuels were studied by different authors(9-12). Fig. 3 gives an impression of the complex nature of the flow field in the dump combustor. The foremost region of the combustor is characterized by a recirculation zone caused by the sudden enlargement of the inlet step. This zone is used for flame stabilization. The length of the recirculation zone is determined by the step height. The second important combustion zone can be described by a turbulent diffusion flame within the redeveloped boundary layer downstream of the reattachment point. The amount of vaporized fuel is determined mostly by the convective and radiative heat transfer from the narrow "flame sheet" to the fuel surface. Fuel vapors from the surface and oxygen-rich gases from the core flow diffuse from opposite sides into the boundary layer. This diffusion-controlled flame is sustained by the hot combustion products of the recirculation zone, which are partly mixed with the increasing core flow; thus the combustion cycle is completed. The dominant parameters for the heat transfer, or the total amount of vaporized fuel, are the air mass flux G_{air}, the chamber pressure p_c, and the air inlet temperature $T_{2,tot}$.

The description of the combustion process in SFRJ combustors using fuels with metal additives differs from the non-metalized situation. Gany and Netzer(13) studied the combustion phenomena of highly metalized solid fuels by means of high speed photography and a windowed two-dimensional SFRJ combustor. Metal additives are usually introduced as fine powders into a matrix of a polymeric binder. The particles tend to accumulate and coalesce at the condensed fuel surface. Thus, large agglomerates are ejected to the gas stream without ignition at the fuel surface, because no oxygen is existing there. The rate of inert heating or the amount of evaporation of the particle depends upon the material. While magnesium, having a very low boiling point, may evaporate at or near the fuel surface, this is not the case especially for boron or boron compounds. The understanding of metal particle combustion in an SFRJ combustor seems to be very difficult, but for achieving high combustion efficiencies with metal-laden fuels more fundamental investigations of these phenomena are necessary.

It was the intention of this study to give an idea on the potential of commonly used hydrocarbon fuels and some fuels with different amounts of metal particles.

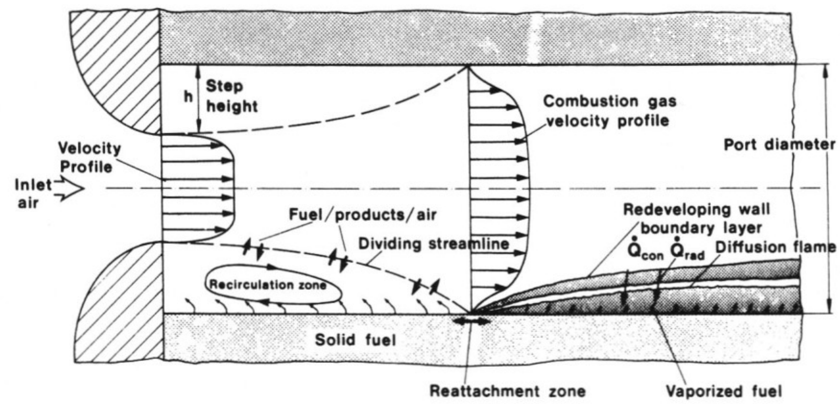

Figure 3. SFRJ Dump Combustor Flow Field

II. Experimental Set-Up and Fuel Manufacturing Procedure

The experimental system consists of an SFRJ combustor and an air heater, which are mounted on a thrust stand (Fig. 4). The air is heated up by the combustion of hydrogen and oxygen. Oxygen is replenished, so that the amount of oxygen is kept constant at 23 percent of the total air mass flow rate.

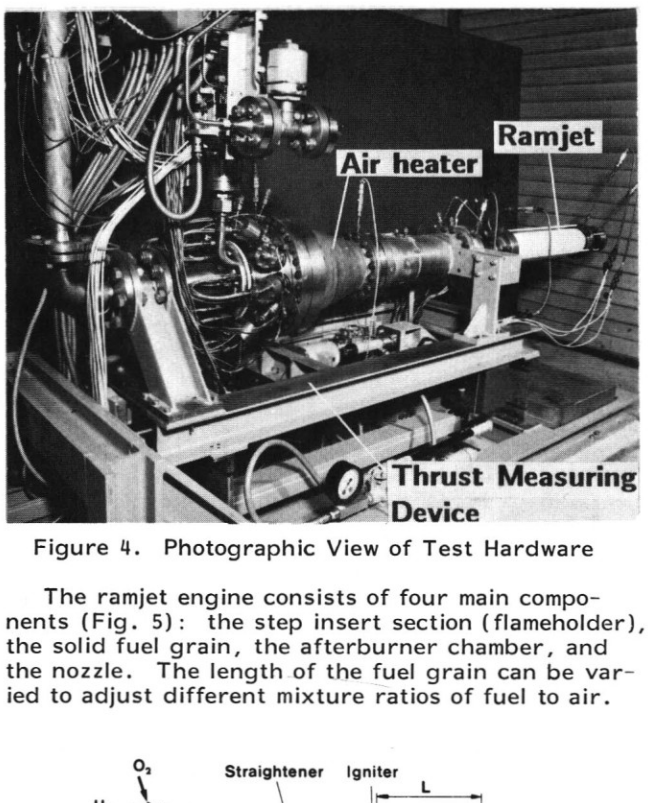

Figure 4. Photographic View of Test Hardware

The ramjet engine consists of four main components (Fig. 5): the step insert section (flameholder), the solid fuel grain, the afterburner chamber, and the nozzle. The length of the fuel grain can be varied to adjust different mixture ratios of fuel to air.

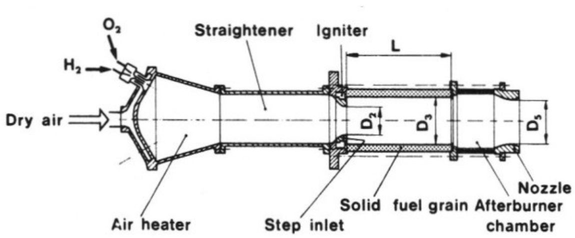

Figure 5. Air Heater and SFRJ Combustor

All tests of this study were carried out at an initial port diameter for the fuel grain of 60 mm. For ignition of the solid fuel, a hot gas (H_2/O_2 spark torch igniter) will be injected into the recirculation zone downstream of the step inlet. Typically, the ignition will be shut off after one second. Several temperatures, pressures and the axial thrust are recorded by a data acquisition system.

To give an idea of the requirements of a ramjet test facility, the combustion chamber entrance conditions in dependence of flight Mach number and altitude are shown in Fig. 6. The simulation range of the DFVLR ramjet test facility is shown as the shaded area in this figure. Flight Mach numbers up to 3.5 at sea-level and up to Mach 4 for altitudes between 10 and 25 km can be simulated.

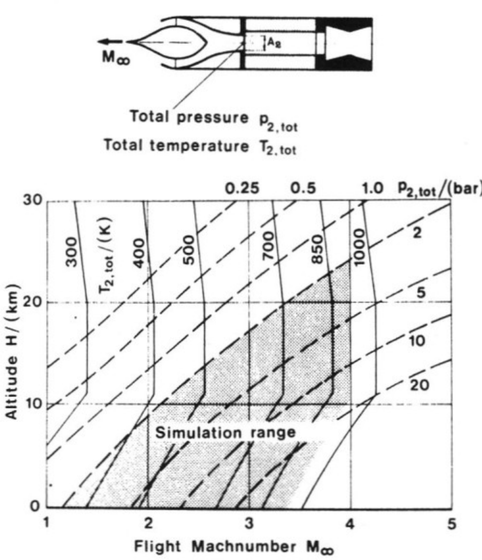

Figure 6. Ramjet Combustor Entrance conditions

Two different methods were applied in order to produce the fuels for this experimental study, casting and pressing. Commercial hydroxyl-terminated polybutadiene ARCO R 45 M was used as a binder for the casting process. The fuel ingredients (metals or polymers) were mixed with the binder by an impeller. During the mixing process the product was heated up to 80 °C, causing a decrease in viscosity. The mixture was degassed under vacuum in a glass vessel. TDI was added as a curing agent; then the mixture was stirred and degassed again. The resulting highly viscous liquid was cast into a cylindrical mould made of reinforced phenol-formaldehyde resin. The cylindrical mandrel was made of polyethylene. The fuels were cured for three days at 80 °C. After storing the moulds for a short time in a refrigerator, the mandrel could be removed by a hydraulic press. No antioxidants were used because the fuel was not stored very long but subsequently fired.

The fuels which were produced by the pressing procedure were treated as follows. The ingredients were mixed in a blade kneader, and the moist mass was filled into a vacuum mould and compressed to fuel blocks by means of a hydraulic press. The fuel grain was made from several fuel block elements.

III. Test Results

As described above, the key factors for the performance evaluation of an SFRJ fuel are the regression rate, fuel density and the gravimetric heat of combustion. To compare different fuels, HTPB was chosen in this study as the baseline fuel. Thus, the energy flux ratio is defined as

$$K = \frac{\rho \cdot \bar{\dot{r}} \cdot \Delta H_c}{(\rho \cdot \bar{\dot{r}} \cdot \Delta H_c)_{HTPB}} .$$

This definition assumes that the released fuel can be completely burnt inside the combustor.

Pure Hydrocarbon Fuels.
For a PE-fuel the regression rate was investigated over a wide range of different flight Mach numbers and altitudes, respectively, at different chamber pressures, air mass fluxes and inlet temperatures. In Fig. 7 an example of the regression rate study is shown. With increasing air inlet temperature $T_{2,tot}$ and chamber pressure p_c the regression rate increases. The experimental data can be approximated by the following power function:

$$\bar{\dot{r}} = 0.008 \cdot p_c^{0,28} \cdot T_{2,tot}^{0.50} .$$

As shown in (9), the influence of G_{air} is of the same order as the chamber pressure.

Test results of the energy flux ratio for different hydrocarbon fuels are shown in Fig. 8. The pure PE- and PMMA fuels, and the HTPB/PS and HTPB/PE mixed fuels have lower energy fluxes than pure HTPB fuels. These tests were carried out at the same test conditions ($p_c \simeq 4.3$ bar, $G_{air} \simeq 13.5\,g/cm^2s$, $T_{2,tot} \simeq 15$ °C). The mixed fuels with HTPB and PAMS show distinctly higher energy fluxes than a pure HTPB-fuel (test conditions: $p_c \simeq 5.2$ bar, $G_{air} \simeq 26\,g/cm^2s$, $T_{2,tot} \simeq 200$ °C). The combustion efficiency is not taken into account in this comparison. Especially the test with the HTPB/PAMS*-fuel showed an exhaust plume with large amounts of soot, so that a larger afterburner chamber or additional mixing devices will be needed to yield a sufficient combustion efficiency.

By increasing the fuel surface with a spoke type grain ($A_s \simeq 2 \cdot A_{cyl.}$), it is possible to increase the fuel mass flow and thus the energy flux.

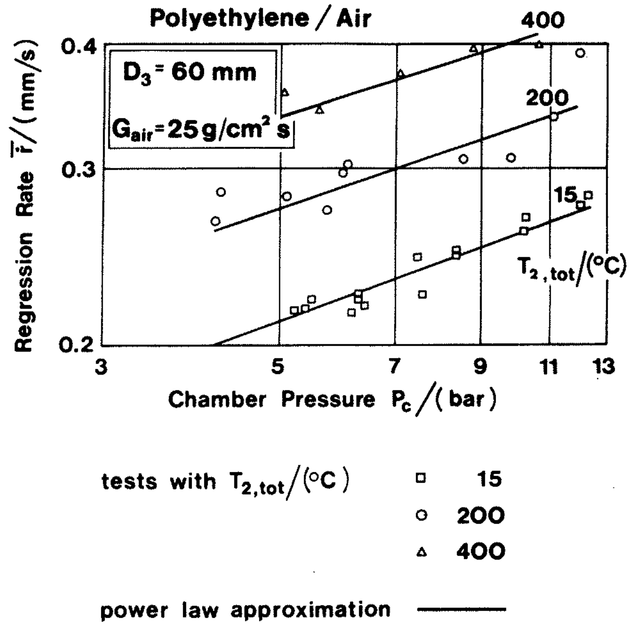

Figure 7. Regression Rate vs. Chamber Pressure for Various Air Inlet Temperatures

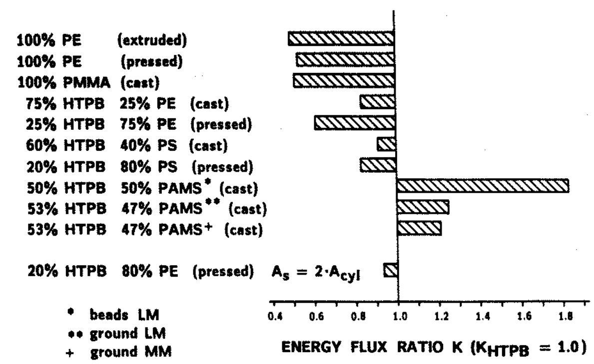

Figure 8. Energy Flux of Different Hydrocarbon Fuels

Fuels with Metal Additives.
A test series with fuels containing different amounts of magnesium are shown in Table 1. Under the same test conditions the regression rate increases with an increasing magnesium content. The density of the cast blend of HTPB and magnesium is up to 9% lower than the theoretical one; possibly the manufacturing techniques used did not allow to produce a fuel without any air inclusions. Adding of wetting agents as additives did not increase the fuel density. The magnesium particles had a diameter of < 100 µm. The gravimetric heat of combustion decreases with an increasing magnesium content, but is outweighed by the gain in regression rate and density.

Test results of fuels with different metal compositions are shown in Fig. 9 (test conditions: $p_c \simeq 3.8$ bar, $G_{air} \simeq 13.8\,g/cm^2s$, $T_{2,tot} \simeq 400$ °C). All HTPB fuels with metal additives have a higher energy flux than the pure HTPB. The HTPB/Al and HTPB/Si fuels show an energy flux maximum, so that an optimum can be assumed for metal portions of less than 50 wt.%. SFRJ fuels loaded with different metal parti-

FUEL/(WT %) HTPB	Mg	ρ (g/cm³)	$\bar{\dot{r}}$ *) (mm/s)	Φ	$\frac{\rho \cdot \bar{\dot{r}}}{(\rho \cdot \bar{\dot{r}})_{HTPB}}$	ΔH_c (kJ/g)	$\frac{\rho \cdot \bar{\dot{r}} \cdot \Delta H_c}{(\rho \cdot \bar{\dot{r}} \cdot \Delta H_c)_{HTPB}}$
100		0.93	0.414	0.95	1.00	42.99	1.00
90	10	0.97	0.419	0.99	1.06	41.16	1.02
80	20	1.02	0.474	1.14	1.26	39.33	1.15
70	30	1.08	0.441	1.19	1.55	37.51	1.35
60	40	1.14	0.597	1.20	1.77	35.69	1.47

*) test conditions: p_c = 5.3 bar, G_{air} = 13.5 g/cm²s, $T_{2,tot}$ = 5 °C

TABLE 1. Test Firings with HTPB/Magnesium Fuels

cles (HTPB/Mg/Si , HTPB/Al/B_4C , HTPB/Mg/B_4C) seemed to improve the performance compared to a blend of HTPB and only one metal type.

Furthermore, two tests with hydrocarbon fuels containing significant amounts of oxidizer are shown (BS / PE / AP, test conditions: $p_c \simeq 5$ bar, $G_{air} \simeq$ 13 g/cm²s , $T_{2,tot} \simeq 5$ °C). These fuel types have distinctly higher regression rates but low heating values.

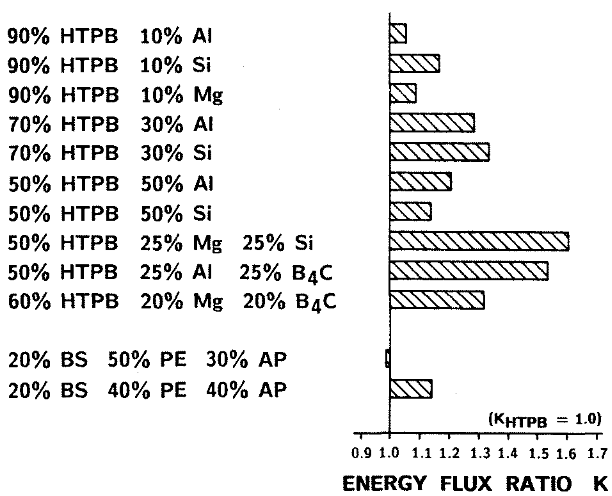

Figure 9. Energy Flux of Fuels with Different Metal Additives

IV. Summary

The energy release of solid fuels has been studied by using a SFRJ combustion chamber equipped with a vitiated air heater. Some properties upon which fuel selection is generally based are discussed. For a PE fuel the regression rate dependence on flight altitude and Mach number, or on air mass flux, chamber pressure and air inlet temperature, respectively, is shown and can be expressed by an empirical power function. The influence of the air inlet temperature is somewhat larger than that of the chamber pressure and the air mass flux. Other experiments with pure hydrocarbon fuels or blends of HTPB with PE, PS or PAMS were carried out, and their energy fluxes were presented in comparison to the HTPB baseline fuel. The investigated regression rate of metalized fuels (magnesium, aluminum, silicon, boron-carbide) shows a considerable increase in performance related to pure hydrocarbon fuels.

V. Nomenclature

A	= area
D	= diameter
G_{air}	= air mass flux ($\dot{m}/A_3$)
ΔH_c	= gravimetric heat of combustion
$\dot{m}$	= air mass flow
p_c	= combustion pressure
$\bar{\dot{r}}$	= average regression rate
T_{tot}	= total temperature
ρ	= density
Φ	= equivalence ratio
AP	= amonium perchlorate
BS	= butadiene-styrene
HTPB	= hydroxyl-terminated polybutadiene
PAMS	= poly-α-methylstyrene
PE	= polyethylene
PMMA	= polymethylmethacrylate
PS	= polystyrene
TDI	= tolylene diisocyanate

Subscripts

2	= flameholder inlet
3	= fuel port
5	= nozzle throat
s	= fuel surface

VI. References

(1) Crispin, B., "Ramjet and Ramrocket Propulsion Systems for Missiles", AGARD-LS-136, Sept. 1984.

(2) Marguet, R., Cazin, Ph., "Ramjet Research in France : Realities and Perspectives", ISABE 85-7022, Beijing, Sept. 1985.

(3) Benson, S.W., "Thermochemical Kinetics", John Wiley & Sons Inc., New York, London, Sydney.

(4) Gund, J.M., Eiji, Osava, Van Zandt, Williams, Jr. and Schleyer, P. v. R., "Diamantane I. Preparation of Diamantane. Physical and Spectral Properties", Journal of Organic Chemistry, Vol. 39, No. 20, 1974, pp. 2979-2987.

(5) Schrauzer, G.N., Bastian, B.N., and Fosselius, G.A., "π-Complex Multicenter Reactions Promoted by Binuclear Catalyst Systems. "Binor-S", a New Heptacyclotetradecane via Stereospecific Dimerization of Bicycloheptadiene", Journal of the American Chemical Society 88, 21, November 5, 1966.

(6) Rabinovitch, B., "Regression Rates and the Kinetics of Polymer Degradation", Tenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, 1965, pp. 1393-1403.

(7) Kumar, R.N., and Stickler, D.B., "Polymer-Degradation Theory of Pressure-Sensitive Hybrid Combustion", Thirteenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, 1971, pp. 1059-1072.

(8) Cullis, C.F., and Hirschler, M.M., "The Combustion of Organic Polymers", Clarendon Press, Oxford 1981.

(9) Schulte, G., "Fuel Regression and Flame Stabilization Studies of Solid-Fuel Ramjets", JPP, 1986.

(10) Schulte, G., Pein, R., Högl, A., "Temperature and Concentration Measurements in a Solid Fuel Ramjet Combustion Chamber", to be published 1986.

(11) Schadow, K.C., Cordes, H.F., Chieze, D.J., "Experimental Studies of Combustion Processes in a Tabular Combustor with Fuel Addition Along the Wall", Comb. Sci. and Techn., Vol. 19, 1978, pp. 51-57.

(12) Mady, C.J., Hickey, P.Y., Netzer, D.W., "An Investigation of the Combustion Behavior of Solid Fuel Ramjets", Naval Postgraduate School, Monterey, Calif., Rept. NPS-67 Nt 77092, Sept. 1977.

(13) Gany, A., Netzer, D.W., "Combustion Studies of Metalized Fuels for Solid Fuel Ramjets", 21st Joint Propulsion Conference, Monterey, Calif., July 1985.