Combustion Studies of Metallized Fuels for Solid-Fuel Ramjets

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Combustion phenomena of highly metallized, boron containing, solid fuels in solid-fuel ramjets (SFRJ) were studied by means of high-speed photography using a windowed two-dimensional SFRJ combustor. The experiments indicated the existence of a gas-phase diffusion flame of the volatile fuel ingredients within the boundary layer above the fuel surface. It was also revealed that material is often emitted from the surface in the form of large pieces and segments. Flow impingement on the surface may cause surface heating and glowing by chemical reactions, which promote the high-speed ejection of hot particles and the emittance and disintegration of large glowing segments and pieces from the fuel surface layer into the gas stream.

Introduction

THERMOCHEMICAL evaluation of fuel candidates for advanced solid-fuel ramjet (SFRJ) systems reveals the high energy and energy density of some metals, especially boron and boron compounds.[1] Compared with the commonly used hydrocarbon (HC) fuels, boron exhibits remarkable theoretical heat of combustion per unit mass (about 30% higher than HCs) and per unit volume (almost three times that of HC). As an ingredient of solid fuels for ramjets, metals, including elemental boron or boron compounds (e.g., boron carbide), are usually introduced as fine powders into a matrix of polymeric material.

In spite of the promising potential, the practical use of solid-fuel formulations highly loaded with metal particles can present severe problems associated with complex burning phenomena, which have major effects on the energy generation process within the combustor and may lead to poor combustion efficiencies and low motor performance.

Experimental investigations and modeling of the combustion of nonmetallized fuels in SFRJ combustors have provided a good description of the main combustion and flow characteristics.[2,3] See Fig. 1a. The foremost region of the combustor is characterized by a separated recirculation flow zone generated by the inlet step used for flame stabilization. Downstream of the reattachment zone, often along most of the fuel grain length, a gas-phase diffusion flame, typically a narrow "flame sheet," is established within the turbulent boundary layer that develops over the condensed fuel surface.[4] Fuel vapors diffuse from the decomposing fuel beneath the flame, while oxygen is transported to the flame from the core stream along the combustor centerline. Heat feedback from the flame to the condensed fuel determines the fuel regression rate and completes the combustion cycle.

The situations encountered when using highly metallized fuels are somewhat different (Fig. 1b). Although the flow characteristics are similar to those existing in the combustor employing nonmetallized fuels, the combustion phenomena are not the same. Metal particles tend to accumulate and coalesce at the condensed fuel surface prior to their ejection into the gas stream. The result may be the formation of relatively large agglomerates. As the fraction of volatiles in the metallized fuels is relatively small (typically 30-50%), the gas-phase diffusion flame is not as intense as that of nonmetallized fuels and it probably plays a less important role in the overall combustion process. As most of the energy release is due to the metal particle combustion, information on phenomena associated with metal particle histories is of major significance for the understanding of combustor operation and combustion efficiency. It is expected that the gas-phase diffusion flame between the fuel decomposition products and the air will be formed closer to the wall. Accordingly, pronounced oxygen concentrations will still exist at a relatively small distance from the wall. However, at the condensed surface itself, it is expected that almost no oxygen will exist. Hence, only "inert" heating of the metal particles at the surface, without ignition, is expected. Ejection of metal particles and agglomerates from the surface may be due to pressure forces or gas flow resulting from the decomposition of the polymeric (volatile) fuel matrix (in some cases also due to metal oxide vaporization), with the aid of cross-flow forces. However, no distinct event such as particle ignition can be the cause, in contrast to the case of solid propellants containing an oxidizer. Under such conditions, metal particles are expected to leave the fuel surface unignited. They continue to heat up while moving into the gas stream and may ignite only when reaching an oxygen-rich zone.

Ignition of metal particles requires certain conditions. The oxide coating, which often exists around the metal particles or agglomerates, slows the reactions between the gaseous oxygen and condensed metal. Volatile metals such as magnesium can ignite at relatively low temperatures. However, rapid oxidation of boron particles requires that the surrounding gas temperature be about 1900 K.[5] In addition, the existence of relatively large agglomerates results in long burning times (typically 20-40 ms for a 100 μm diam particle) that may be too long compared with the residence times in the motor. In such cases, incomplete combustion and lower motor performance will result. The burning particles, which are dispersed throughout the combustor volume, transmit heat mainly via radiation to the wall.

In order to provide some reasonable description of the metallized SFRJ combustor operation, metal particle behavior, the ejection event, agglomerate sizes, particle trajectories, ignition time and location, and other combustion phenomena should be known in detail. The purpose of this investigation was to obtain some initial fundamental

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characteristics of metal behavior in the SFRJ combustor environment. This type of data is currently needed for combustion model development.

Experimental Approach

The experimental system consisted of a windowed, two-dimensional solid-fuel ramjet combustor with two fuel slabs 20 cm long and 5 cm wide (Fig. 2). Other dimensions were: air inlet height 12.7 mm, combustor port height 25.4 mm, inlet step height 6.35 mm. Air heated to approximately 600 K by means of a methane-air heater (with oxygen makeup) was introduced into the combustor at flow rates of 20-150 g/s and mass fluxes of 1.5-10 g/cm^2·s) (~0.025-0.15 lb/in.^{2}·s). (The chamber pressure was varied from 0.4-1.0 MPa (60-150 psia). Fuels containing high contents of metals, e.g., boron, boron carbide, magnesium, or other metal additives, in an HTPB polymeric matrix have been tested. Specific data presented herein are for B_4C/Mg/HTPB, with equal weight percentages of the two metals.

High-speed motion pictures of the burning fuel surface and the adjacent gas flowfield were taken through nitrogen purged polymethylmethacrylate (PMMA) (Plexiglas) windows, using a Hycam camera at framing rates of 2000-5000 frames/s. The photographed field of view was approximately 10 mm wide. An external light source (2500 W xenon arc) was used to illuminate the condensed fuel surface and the particles and agglomerates moving in the flowfield.

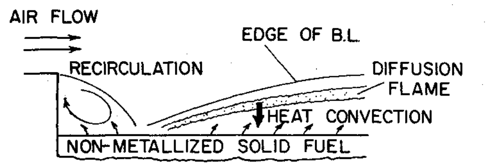
Two different fuel arrangements were tested. In the first configuration, a small piece (approximately 5×2 cm) of the metallized fuel was embedded in a nonmetallized PMMA fuel slab at a position that could be observed from the window. The idea was to avoid the large number of metal agglomerates in the field of view, which could obscure the details of the individual particles in the continuum if whole-metallized fuel slabs were used. The disadvantage of this arrangement was that the extensive gas-phase diffusion flame, originating from the combustion of the nonmetallized fuel upstream of the metallized fuel piece, could affect the flow and temperature fields above the metallized fuel. Hence, a second configuration was then examined, in which a whole-metallized fuel slab was placed in the combustor to provide more realistic conditions.

Two-dimensional SFRJ combustors are not as easy to operate as axisymmetrical ones. This is mainly due to heat loss to the side walls and the lack of sufficient gaseous fuel and heat generation within the recirculation zone. In the higher flow rate experiments, it was difficult to sustain stable combustion in the motor. The problem was solved by injecting a very small flow rate of gaseous fuel (ethylene), of the order of 4-8% of the overall stoichiometric fuel-to-air ratio, into the recirculation zone. The fuel was injected from the side walls, perpendicular to the flow direction. This amount of gaseous fuel was equivalent to the flow rate of gaseous fuel generated from a short section (only 2-3 cm long) of the decomposing solid fuel slab during burning. Ignition of the motor was accomplished with an ethylene-oxygen ignition torch together with the ethylene injection.

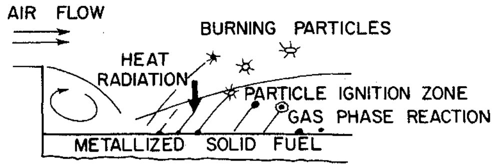
A data acquisition system recorded the air and different gas flow rates, temperatures, and chamber pressure. The films revealed surface phenomena, particle behavior and trajectories, and combustion characteristics.

Results and Discussion

In the two-dimensional combustor configuration used, the flow reattachment region at the end of the recirculation zone was approximately 2-2.5 cm (~ 4 step heights) downstream of the combustor inlet plane. The test section photographed was about 15 cm downstream, where a developed boundary layer was expected to exist. In general, all metallized fuels investigated were more easily ignited and exhibited more uniform combustion behavior at higher pressures.



a) Nonmetallized fuel.



b) Metallized fuel.

Fig. 1 Combustion and flow characteristics in the SFRJ combustor.

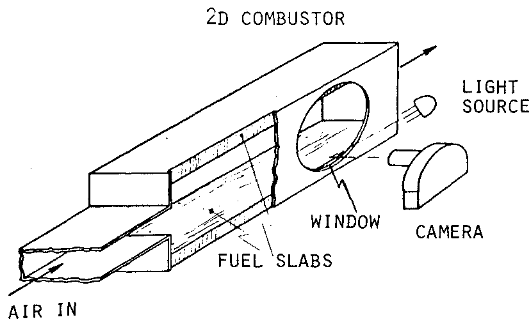


Fig. 2 Schematic of the two-dimensional SFRJ combustor test system.

Gas-Phase Combustion

In accordance with data on the combustion of nonmetallized fuels, the characteristic features of a gas-phase diffusion flame within the boundary layer over the fuel surface were observed for the configuration in which PMMA fuel slabs with only small sections of metallized fuel were used. Intense, orange, luminous flames of a few millimeters thickness were established over each of the fuel slabs (upper and lower) with a complete separation between them indicated by a dark core flow.

When using highly metallized fuel slabs containing only a fraction of volatile polymeric material, there was still an indication of a gas-phase diffusion flame, but the gas-phase combustion was faint, much less luminous, thinner, and almost transparent. In addition, it exhibited a somewhat periodic behavior, where for a while luminosity would increase and in other instances it would totally disappear. Motion pictures of a motor operated at an air mass flux of 10 g/s·cm^2 and a pressure of 0.4 MPa (60 psia) showed that, over a large number of flame luminosity cycles, the characteristic period time was about 7.5 ms. Possibly, this behavior was associated with processes that took place in the upstream combustor sections, i.e., the recirculation zone. Future studies will be directed at this region.

Surface Processes and Particle Behavior

The high-speed motion pictures did not indicate continuous fuel surface regression or a steady flux of ejected particles in the region under observation (in contrast to regular metallized solid rocket propellants). The same behavior was typical to both the low air mass flux (2 g/s·cm^2) tests, which used a small section of metallized fuel embedded in the nonmetallized fuel slab, as well as to the higher mass flux (10 g/s·cm^2) tests, where whole metallized fuel slabs were used. Most of the material ejected from the surface in the zone under observation seemed to be in the form of relatively large fragments or segments of the condensed fuel. Such pieces left the surface sporadically, usually unignited. They moved in low trajectories and were often disintegrated in the gas stream. The ejection events seem to be the result of local looseness of the connection between the upper layer and the underlying material, combined with forces applied by the gas cross flow. This behavior was characteristic of the B_4C/Mg fuel, but not as often observed for other fuels such as Ti/B. A similar characteristic mass loss mechanism has been observed during the deflagration of highly metallized, fuel-rich solid propellants.[6] Figure 3 presents a sequence of pictures showing a typical ejection of a nonburning fuel piece. The low trajectories of ejected pieces shown in the figure (often including rolling on the surface) prevent fast oxidation and heating due to the low oxygen concentrations in regions adjacent to the surface.

Different, interesting surface phenomena were observed under specific conditions. In some cases, where bumps or surface roughness existed, glowing of the surface occurred, indicating local heat release by chemical reactions. It was concluded that under regular flow conditions almost no oxygen exists at the condensed fuel surface. However, if due to surface waviness less or other circumstances (local) impingement of higher oxygen concentration gas on the fuel surface occurs, then surface heating due to chemical reactions can take place. The understanding and control of these phenomena may be quite significant, as they affect the fuel regression process and may promote the ejection and ignition of metal particles and fuel pieces. The development of a glowing surface zone was a continuous process. It may start from a small spot and then spread out and grow. Figure 4 presents a series of pictures showing the development of a glowing surface zone. The onset of glowing was at the upstream side of the peak of a 1/3 mm high bump on the fuel surface. It spread out and achieved a size of 2.5 mm after 65 ms and became 4.5 mm wide and almost 1 mm thick after 200 ms.

Hot surface zones were often the site of special surface activity. As mentioned previously, in general, the ejection of individual metal particles from the surface was rare. However, when the surface was hot (glowing), the situation was different and particles were themselves very hot when they left the surface. In addition, the particles were often ejected in all directions at a relatively high initial speed. The ejections usually took place as bursts of a number of particles. Both the high initial speed (especially if it had a significant component perpendicular to the surface) and the high initial temperature of the particles are very significant, as they enable the particles to quickly reach high oxygen concentration zones at high temperatures, conditions necessary for ignition and flame development. It is believed that particle bursts from the hot glowing surface are the result of pressure developed within the hot bulk by gases generated from the volatile ingredients due to the high temperature. Bursts were of different strengths. In some of them, the typical initial ejection speed of the particles was 2-3 m/s, on average it was 6-8 m/s, and in the strong ones up to 15-20 m/s. Measurements showed particle ejection directions from 0 deg (i.e., axial flow direction) to about 170 deg (almost against the gas flow direction). Typically, during a single particle burst, directions were confined within a section of about 90 deg. Figure 5 shows a burst of particles from a glowing surface zone. Initial particle speed was of the order of 15-20 m/s and ejection directions were between 30 and 74 deg to the axial flow. Surface heating, if it occurs, may also cause ejection of large hot condensed pieces into the gas stream (see Fig. 6).

Experiments with whole metallized fuel slabs indicated an almost continuous high particle flux coming from upstream. It is suspected that these particles originated at the flow reattachment zone, where the inlet flow directly impinges on the surface. This impingement probably causes surface reactions and heating that result in ejection of fuel segments and particles. The reattachment zone exhibited the highest regression

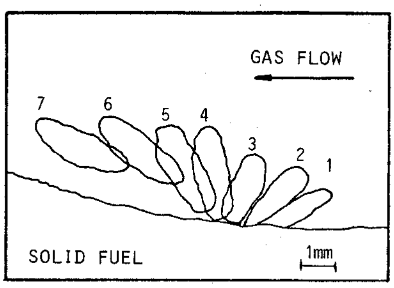


Fig. 3 Sequence of pictures showing the ejection of a nonburning fuel piece at time intervals of 0.25 ms ($G = 10$ g/s·cm^2, $P = 0.55$ MPa).

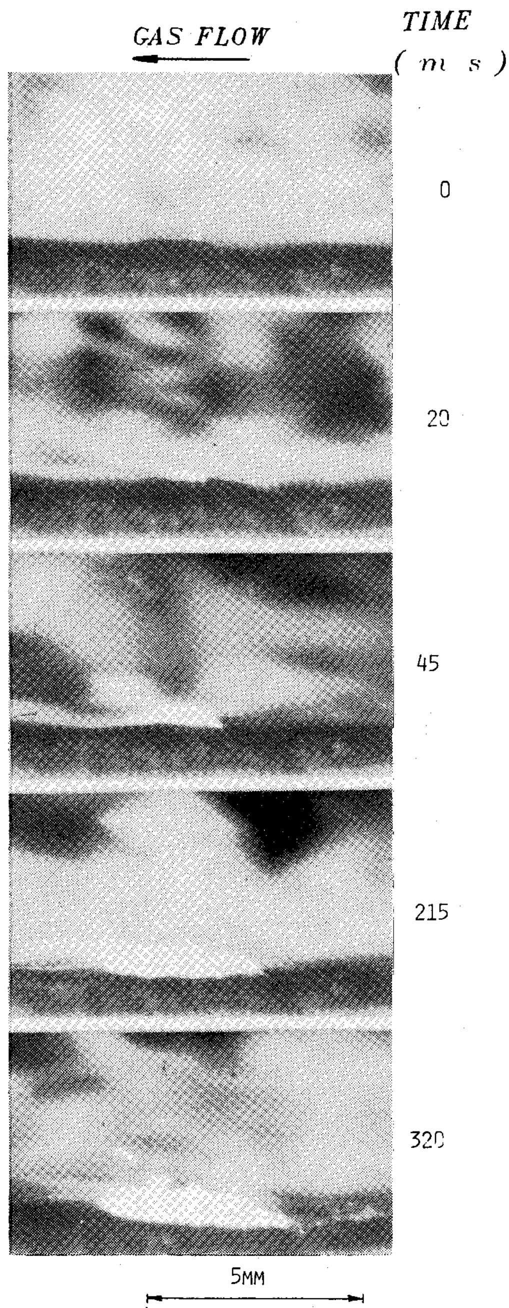


Fig. 4 Development of a glowing surface zone resulting from impingement of the flow on a 1/3 mm bump on the surface ($G = 2$ g/s·cm^2, $P = 0.55$ MPa).

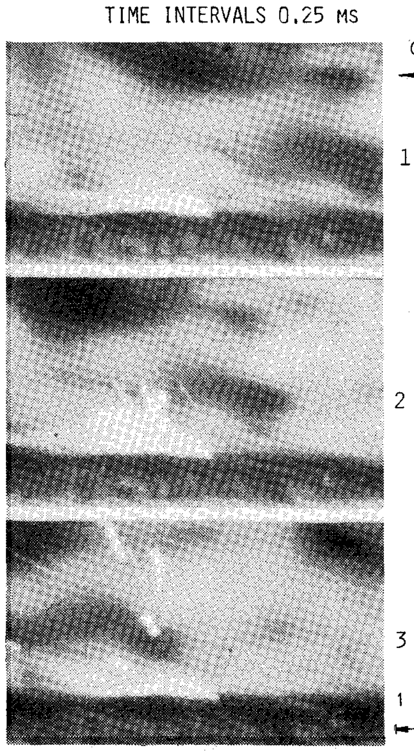


Fig. 5 Burst of particles from a glowing surface zone (initial ejection velocity 15-20 m/s, $G = 2$ g/s·cm^2, $P = 0.55$ MPa, time intervals of 0.25 ms).

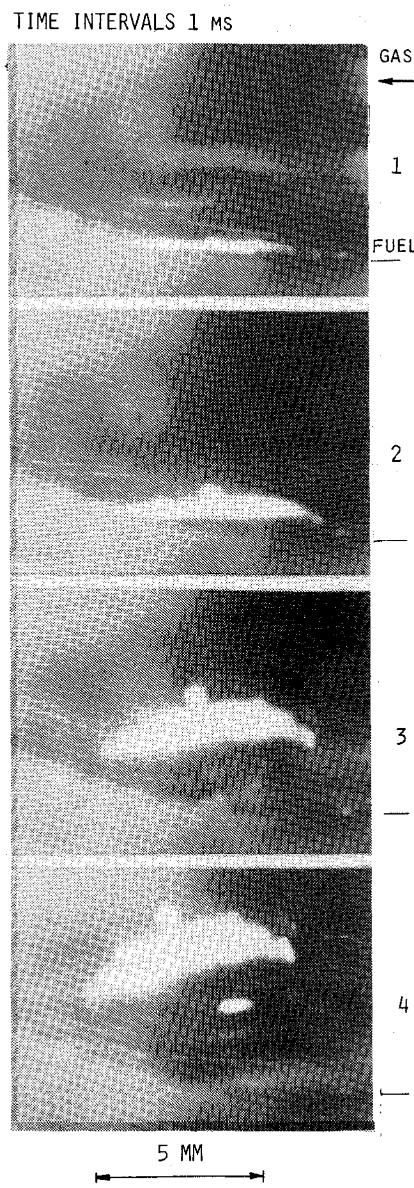


Fig. 6 Ejection of a large glowing fuel segment ($G = 10$ g/s·cm^2, $P = 0.55$ MPa, time intervals of 1 ms).

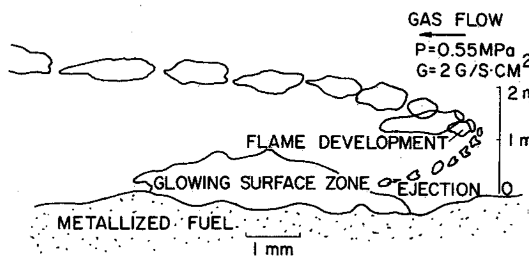


Fig. 7a Composition based on a series of 16 photographs showing the apparent image of a 100 μm particle ejected from a hot glowing surface zone (time intervals of 0.25 ms).

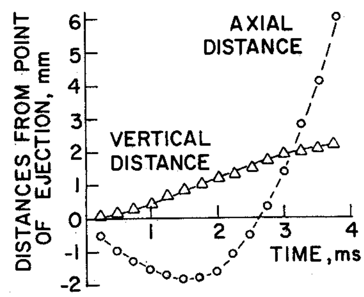


Fig. 7b Axial and vertical distances of the ejected particle vs time.

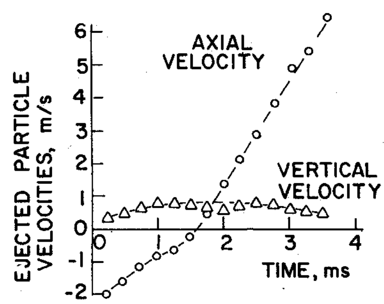


Fig. 7c Axial and vertical velocities of the ejected particle vs time, indicating a sharp increase in particle acceleration at a distance of about 1 mm from the surface.

rate. However, no observations of this region were made during the present investigation.

Trajectories, ignition, and combustion characteristics of ejected particles and agglomerates can have a major effect on the motor operation and performance. Tracking the motion of ejected particles in the gas stream can give information on the temporal variations of particle location, velocity, and acceleration, as well as on ignition location and time and flame development around the particle. Figure 7a is a composition based on a series of 16 pictures taken at a rate of 4000 frames/s. The apparent image of an individual particle of about 100 μm size is sketched at time intervals of 0.25 ms, starting at its ejection from a hot glowing surface zone into the gas stream. The figure reveals that, although the particle was hot when ejected, ignition and flame development around it did not occur during the first 1.5 ms after ejection. The ignition event, characterized by the first appearance of a large bright flame bursting from the particle, happened abruptly when the particle was at a distance of 1.0 mm from the condensed fuel surface. After an 0.5 ms transient situation, a very bright, intense flame was established around the particle. The apparent size of the flame was then about 400 μm, approximately four times larger than the particle size. Figure 7b shows the variation of axial and vertical distances of the particle from its ejection point. Figure 7c presents the changes in axial and vertical velocities of the particle with time. The figure reveals that during the first 1.5 ms, when the vertical distance of the particle from the surface was less than 1 mm, the average particle axial acceleration due to the gas flow was about 1400 m/s^2. The acceleration seems to sharply increase above this distance to about 3400 m/s^2. This gives an indication of the axial gas velocity distribution within the boundary layer near the surface. Another observation was that the vertical particle velocity remained approximately constant (0.6 m/s) for about 4 ms.

Conclusions

The windowed, two-dimensional solid fuel ramjet combustor described in this paper permitted the visualization of the surface and gas-phase processes during combustion. Study of the combustion of highly metallized, boron containing fuels by means of high-speed photography reveals phenomena and mechanisms associated with the combustion process that may greatly influence the motor operation and performance. Material was often emitted from the condensed fuel surface into the gas stream in the form of segments and pieces. Usually, ignition of metal particles did not take place on the surface. Impingement of oxygen containing gas on the surface due to surface roughness or waviness may lead to surface heating and glowing by chemical reactions. Such hot surface zones are the site of surface activity, e.g., shooting of particles at high speed into the gas stream or ejection of large glowing pieces of fuel.

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References

[1]Gany, A. and Netzer, D.W., "Fuel Performance Evaluation for the Solid-Fueled Ramjet," *International Journal of Turbo and Jet Engines,* Vol. 2, 1985, pp. 157-168.

[2]Meyers, T.D., "Special Problems of Ramjet with Solid Fuel," *Ramjet and Ramrocket Propulsion Systems for Missiles,* AGARD Lecture Series 136, Sept. 1984.

[3]Mady, C.J., Hickey, P.J., and Netzer, D.W., "Combustion Behavior of Solid-Fuel Ramjets," *Journal of Spacecraft and Rockets,* Vol. 15, May-June 1978, pp. 131-132.

[4]Williams, F.A., *Combustion Theory,* Addison Wesley Publishing Co., Reading, MA, 1965, pp. 296-305.

[5]Faeth, G.M., "Status of Boron Combustion Research," U.S. Air Force Office of Scientific Research, Washington, DC, Oct. 1984.

[6]Laredo, D. and Gany, A., "Combustion Phenomena of Highly Metallized Solid Propellants," *Acta Astronautica,* Vol. 10, 1983, pp. 437-441.