status and future trends in HIGH SPEED

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Anyone who has observed the pace of rocket and airplane development during the past decade is naturally impelled to ask what can be expected in this field during the next ten years. This survey attempts to answer that question by examining the status of the five areas of chemical propulsion that are now receiving active research support for their potential use for high speed propulsion during the period of the 1970's. Such use will add to the military strength of the United States and will contribute to the growth and stability of the civilian economy.

At the outset it should be noted that propulsion developments have been based on two different scientific disciplines and, as a result, the personnel in the two fields hardly speak the same language. Rocket engines have been the province of the chemist and chemical engineer, while jet engines, which use air, have drawn sustenance from the aerodynamicists and aeronautical engineers. In rocket development there has been major concern with propellant chemistry—formulation of new oxidizers, new fuels and new binders, thermodynamic computations, and studies of combustion characteristics as related to injector design in liquid systems and to grain design in solids. For jet engines the basic problems have been mainly those of the interaction of a moving fluid with the engine mechanism. Problems of heat addition have required constant attention and thought, but for the most part they have been secondary to those of inlet, compressor, diffuser, turbine, and flame holder design, all designed to minimize entropy gain in the fluid stream.

Both rocket and jet engine development have made major demands on metallurgists and structural engineers for new materials and techniques. But here again the problems and new developments have differed so much that they have become almost unrelated fields of endeavor. Rocket engineers have been primarily concerned with the development of lightweight pressure vessels and

During the past decade the concentrated effort to develop better solid and liquid propellants has resulted in improvements in rocket propellant performance to a level which is now near the maximum attainable. While further improvements are possible, a survey of the field of chemical propulsion indicated that other approaches should be considered. Air augmentation, involving injection and combustion of ambient air ducted into the fuel-rich exhaust gases of rockets, may provide greater gains at less cost. There are potentially even greater gains in performance with hypersonic airbreathing vehicles, as they carry only the fuel while other systems must carry all or part of the oxidizer. Recent progress in research on supersonic combustion supports the feasibility of very-high-speed flight vehicles powered by supersonic combustors.

CHEMICAL PROPULSION

with nozzle heat transfer problems, which have been solved by cooling in liquid systems and by the use of refractory metals, graphite, and ablative materials in solid systems. In the airbreathing field, air cooling has been employed to restrain structural temperatures to those for which stainless steel and super-alloys have been adequate.

The lack of communication between the two fields of propulsion has produced such divergence of points of view that, until recently, separate industries and even separate scientific journals were concerned with rockets versus airbreathing systems. Only rarely has a broad enough analysis been made of the potential components of a new propulsion system to permit a truly optimum design to be achieved. An important objective of this paper, therefore, that deals with problems in both types of propulsion, is to focus interest on the whole range of highspeed chemical propulsion possibilities, bringing out the potentialities as well as some of the major problems in a context that embraces all of the principal types that are adapted to high speed flight. "High speed" in this paper is arbitrarily defined to be speed in excess of Mach 5—thus turbojet engines are excluded.

In the rocket field itself a similar bifurcation has existed between "true believers" who espoused liquids (or solids) and "heretics" who endorsed solids (or liquids). Both camps failed to recognize for a long time that hybrid combinations of liquid and solid rocket systems could have advantages (as well as defects) that neither of the purebred systems possessed. Finally, combinations of rockets and airbreathing systems are possible, including the use of rockets for the boost of a ramjet to flight speed, as in the Talos missile, air augmentation of the rocket thrust, and finally, the air collection system known as LACE. This combines in one vehicle a liquid-hydrogen-fueled ramjet and a hydrogen-oxygen rocket. After take-off on rocket power, the vehicle converts to a hydrogen-fueled ramjet at Mach 2 to 3 and accelerates

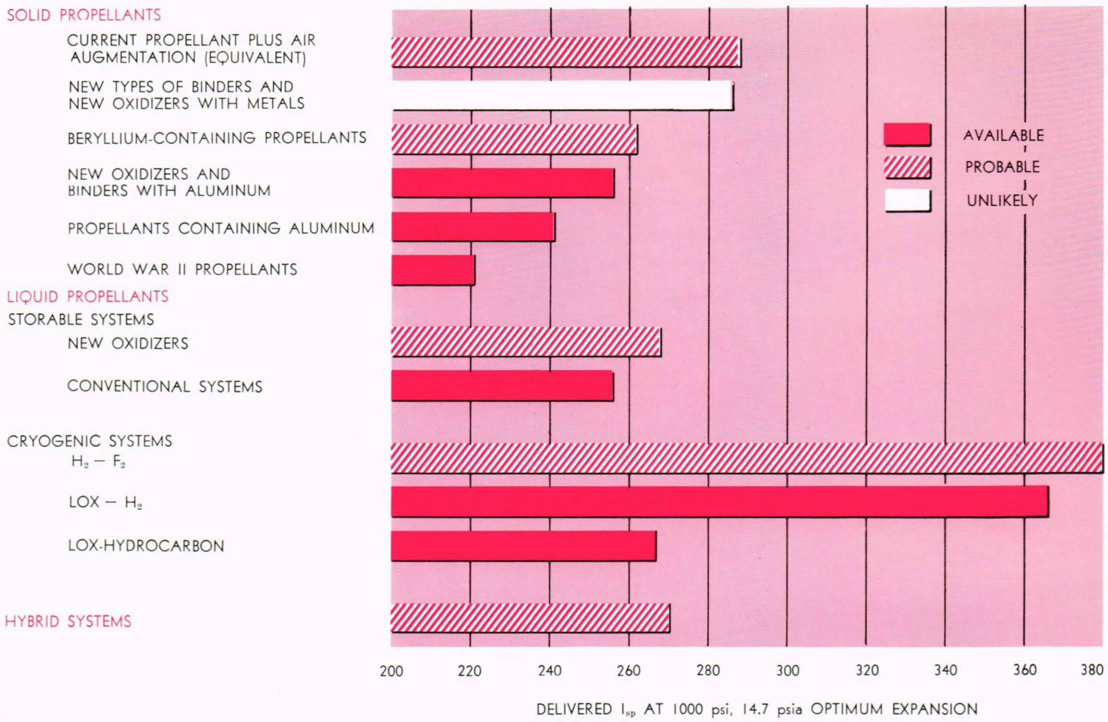

Fig. 1—Trend in delivered specific impulses for various solid and liquid chemical propellants, with values adjusted to sea level at 1000-psia chamber pressure.

to Mach 5 to 7. Cruising at this speed, it collects air, liquifies it with the liquid hydrogen, separates the nitrogen, and stores the liquid oxygen in the now empty tanks used earlier in the flight to contain the propellants. When sufficient liquid oxygen has been collected, the vehicle then returns to rocket power for acceleration into orbit. Unfortunately, space does not permit presentation of a detailed account of this interesting program.

It has already been implied that solid rockets, liquid rockets, hybrid rockets, jet engines, and air-augmented rockets are all members of one not-too-happy family. A systems analyst trained in applied psychology could do great good in getting all propulsion scientists on friendly speaking terms.

After these philosophical comments, the status and future trends of each field will be discussed. Following a logic established by the Greeks, the discussion will start with solids, consider liquids next, and finally air—fire being a common element.

Solid Rockets

From World War II until recently the majority of solid rockets were based on the use of nitrate esters (nitroglycerine-nitrocellulose) or ammonium perchlorate as the oxidizing constituent in combination with a variety of polymeric materials which served both as the fuel and as the binder to give mechanical strength to the propellant grain. These systems gave a delivered specific impulse (I_{sp})* in the range of 200 to 225 sec but were limited in ambient temperatures at which they could be used by the dependence of burning rate on temperature and pressure and by the variation of physical properties with temperature. Both composite and double-base propellants† were plagued with unexplained erratic combustion, which severely limited flexibility of use and caused concern about safety and reliability.

Roughly five years ago a new era began that was characterized by the need for high specific impulse to meet long-range ballistic-missile requirements and by the realization that a well-supported fundamental study of combustion instability was essential to a sound future development of solid rockets. Outstanding progress in understanding this complex problem has been made in recent

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* The specific impulse is the thrust in pounds produced by ejection of one pound of combustion products per second.

† *Double base propellants* consist essentially of nitrocellulose and an explosive plasticizer, usually nitroglycerin. *Composite propellants* consist of a crystalline oxidizer suspended in a polymeric binder. *Composite modified double base* is a term frequently used to designate a composition consisting of a crystalline oxidizer in a nitrocellulose-explosive plasticizer binder.

years[1] by a concerted attack by the three military services and the NASA. The new push toward higher performance was implemented almost at once by the recognition that the addition of aluminum to solid propellants made possible major gains in both specific impulse and burning stability, permitting the I_{sp} of usable propellants to be advanced to a level near 240 sec. Meanwhile the search for new oxidizers and binders produced several attractive compounds, some of which have been incorporated in solid propellants to give further I_{sp} improvement. Polymeric materials suitable for propellants have also steadily improved. Present propellants, therefore, not only give good performance but also have satisfactory physical properties over the limited temperature range needed for the ballistic missiles that demand the highest rocket performance. Figure 1 lists the characteristics of several typical compositions and indicates future trends.

Since the fraction of total rocket weight that is available for propellant depends on the density of the propellant, the best propellant combines high density and high I_{sp}. Unfortunately the two characteristics are to some extent mutually exclusive so that the best compromise must be selected. The relative value of the two characteristics depends on the application. The optimum for volume-limited systems lies near the maximum of the product of I_{sp} and density. Figure 2 shows a plot of I_{sp} versus density for a selection of propellant types that offer the best options for a range of I_{sp} and density values; also shown are the ranges potentially available in 1970.

Thermodynamic evaluation of potential ingredients which have been intensively studied during the past five years furnishes boundaries to the possible improvement that may be expected from development of improved ingredients. Since the specific impulse involves primarily the heats of formation and recombination of the propellant ingredients, as well as the elemental atomic weights, the upper limits can be narrowly defined. No combination of solid ingredients offers theoretical I_{sp} (based on 1000-psi chamber pressure and expansion to 14.7 psi) significantly greater than 300 sec at a density equal to that of the best current propellants. With 95% efficiency of energy release, the predicted maximum delivered I_{sp} will be 285 sec or less. Compositions employing beryllium rather than aluminum will probably provide performance improvement, although there is some loss in density. Probably the optimum propellant of this type would use aluminum and beryllium at a ratio maximizing the I_{sp} density product.

Propellants based on future oxidizers and new types of binders now in the test tube stage may give still greater I_{sp} gains approaching the theoretical maximum goal. However, at present no suitable techniques exist for preparing combinations of the ingredients that are safe to handle and stable in storage. The technology is relatively undeveloped, and improvement may be expected if cost effectiveness studies do not eventually prove that alternative methods will meet future propulsion requirements at lower cost.

Three recent developments of great interest, that do not involve improvement in propellant I_{sp} but significantly increase rocket performance and effectiveness, have been made.

The first of these stems from recognition of the fact that the metals used in modern propellants to enhance I_{sp} can be incorporated in a way that will increase the propellant strength by a factor of 100 to 1000, giving the propellant ability to withstand an appreciable fraction of the internal pressure in the rocket case. With a tailored pressure-time curve, the inert weight of the rocket may then be reduced, with a consequent improvement in the burnout velocity. Payload gain of up to 10% in a typical ballistic rocket application may be possible by this means.

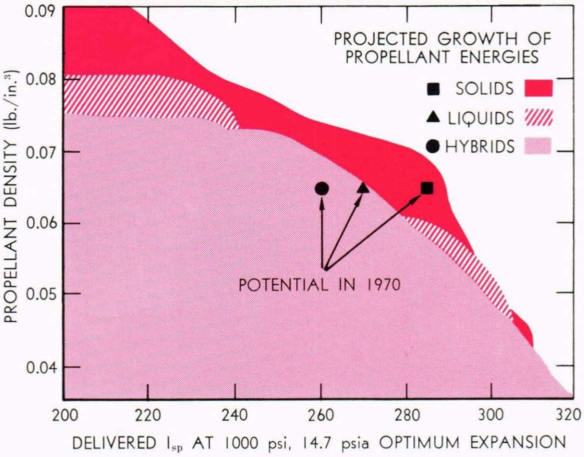

Fig. 2—Range of specific impulse and density values for chemical propellants. The three small geometrically shaped areas are for propellants that are potential in 1970.

The second development of major interest is the extension in propellant burning rates that has been achieved by incorporation of metal wires in the propellant mix. These are variations of the "control strands" investigated during World War II as a means of increasing burning rates. The wires

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[1] W. G. Berl, "Instability in Solid Rockets," *Astronautics and Aeronautics*, **3**, Feb. 1965, 54-62.

conduct heat into the propellant surface, thereby increasing the local burning area, and consequently increasing the apparent normal burning rate. Reproducible performance at high burning rates has been achieved in both composite and composite-modified double-base formulations by this means. The requirement for these high burning rates has developed in connection with high speed missiles. There are several applications wherein accelerations at upwards of 100 g to reduce flight time to the absolute minimum are required. As a result of this work, end-burning grains for missile use have also become possible, offering the possibility of further improvement in mass fraction.

Finally, the development of very large solid rockets is requiring extension of manufacturing technology, particularly in those aspects involved in propellant and pressure-vessel fabrication. New approaches will be needed that will minimize requirements for huge equipment and that will insure safety in manufacture, reproducibility of performance, and feasibility of transportation. Use of segmented or building-block grain configurations appears to offer the best solution for the propellant problem. The problems with nozzle erosion are lessened in these large motors. Ablative materials may be used in the throat area because the area change associated with ablation is an insignificant part of the total nozzle area.

The above review suggests the following areas for future research and exploratory development emphasis in the solid-propellant field:

1. Advancement of the chemistry of oxidizers and fuels. New materials have been synthesized that could extend propellant I_{sp} to delivered values in the range of 270 to 285 sec without density loss. However, it will be necessary to demonstrate that propellants based on them can be manufactured cheaply and safely and can have long-term chemical stability.
2. Investigation of methods of augmentation of burning rate to values above 5 in./sec.
3. Development of methods for incorporating metallic ingredients to improve propellant strength; and investigation of the resulting internal ballistic effects.
4. Continuing research on combustion instability to provide quantitative chemical and physical requirements for systems that will guarantee stable operation.

Liquid Rockets

Since the first experiments by Dr. Goddard, liquid rocket systems have occupied a pre-eminent position for applications requiring the maximum possible terminal velocity. The first large ballistic missiles were powered with liquid rockets, and the present space program depends almost entirely on liquids for its vehicle launching requirements. The high performance of liquid rockets derives from two factors. (1) Theoretically attainable I_{sp} is higher than in solids; the cryogenic hydrogen-oxygen and hydrogen-fluorine systems will probably yield an I_{sp} near 400 sec, while the best value for solid propellants will be about 300 sec at the same conditions. Many storable liquid systems could provide specific impulse above 270 sec (with the combustion chamber pressure being allowed to drop from 1000 psi to 14.7 psi). (2) The inert weight of liquid systems can be lower than that of solids because the propellant tanks do not have to withstand the combustion chamber pressure. In addition, thrust of liquid rockets can be controlled, including rapid shutdown of thrust. These advantages that solids have not been able to match have been offset in military applications by the difficulty of providing instant readiness and by the inherently greater complexity of the liquid engines, which necessitates extreme precautions in checkout procedures to guarantee reliability. Cryogenic systems require particularly stringent procedures.

Recent years have witnessed a trend away from cryogenic liquids in military systems. At present the only Navy applications of liquid rockets are the small units based in their LR 64 target drone and in the Bullpup missiles. For these aircraft applications storable liquid rockets have fulfilled an exacting performance requirement not met by available solids. These rockets have shown that storable liquid propellants can be fully competitive with solids in meeting the requirements for instant readiness, reliability, cost, and performance. The engine used in Bullpup has demonstrated an extremely high reliability. The engine is delivered with propellants hermetically sealed in the tanks at a cost of \$6.25/lb. Cryogenic liquid rockets provided by the Air Force are used as boosters for the Navy's satellites, but these would undoubtedly be replaced by solids or storable liquids if a requirement for launching at sea should develop.

Propellant combinations of most current interest in the liquid rocket industry[2] include the following:

1. Nitrogen tetroxide with a 50-50 mixture of hydrazine and unsymmetrical dimethylhydra-

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[2] M. W. Hunter II, A. O. Tischler, F. A. Williams, and E. W. Price, "Launch Vehicles and Missiles," *Astronautics and Aerospace Engineering*, 1, Nov. 1963, 46-53.

zine is employed in the Titan II,[‡] which is planned for use in the military space program. It is interesting that this rocket will be uprated to the Titan III by addition of solid-propellant auxiliary engines. If rapid launching of space vehicles were to become of direct military importance it is probable that a solid rocket would replace the Titan II engine.

2. The hydrocarbon-oxygen propellant system employed originally on a large scale in the Atlas missile will be used in the F-1 engine, which will be the first U. S. rocket to deliver more than 1 million pounds of thrust. Five of these in a cluster will comprise the first stage of the Saturn V space launch vehicle.
3. Liquid hydrogen and liquid oxygen will be used in upper stages of the Saturn lunar launch vehicles and in the multi-purpose upper stage Centaur vehicle. The A-3 engine with 15,000-lb thrust was successfully flight tested in November of last year. It will be followed by a larger version (J2) now in development, with 200,000-lb thrust, and eventually by a still larger engine (M1), with nominally 1.5 million pounds of thrust. For maximum thrust, plans are being made to operate this engine at combustion-chamber pressures above 2000 psi.
4. The combination of mixed amines and inhibited red-fuming nitric acid has been used in various Aerobee missiles and is in current use for versions of Bullpup.
5. A new oxidizer has recently been approved for shipboard use as a result of tests that show that its handling hazards are no greater than those of combination (4) above. The propellant I_{sp} and density make it very attractive for volume-limited applications.

A problem that, since the earliest American work, has plagued liquid engine development as well as solid, has been the occasional occurrence of very destructive pressure oscillations in the combustion chamber. A major achievement of the past year has been the formulation of design methods that prevent the occurrence of these oscillations and of tests that satisfactorily demonstrate the stability of the combustor performance. This is of great importance in reducing the development cost of advanced systems.

Development work is continuing on fluorine and its compounds as a means of attaining the maximum possible upper-stage capability. Studies are also active on systems employing slurry fuels that offer gains in impulse per unit volume. However, apart from the engineering effort to increase the total thrust of current engines, the principal effort on the liquid systems is devoted to improvements designed to give better reliability, lower combustion chamber weight, and lower cost.

As in the case of solid rockets, liquid systems are now operating at levels within 10% of the theoretically attainable performance. This, combined with the enormous investment in the current high-performance systems, makes it unlikely that major new liquid-rocket programs will be started for space applications in the near future.

The investment in silos and submarines for the Minuteman and Polaris systems will place on future missiles a requirement for the most efficient use of the existing launch tubes. The generally lower density I_{sp} of liquid systems, compared with solids, rules out conventional storable liquid systems; however, some newer liquid combinations may merit study. For example, slurries of light metals in mixed hydrazines with a dense oxidizer could be attractive if a cost effectiveness advantage could be demonstrated.

The need for instant readiness will rule out nonstorable liquid systems for military applications. However, for tactical Navy missiles such as Bullpup or the projected Condor missile, storable liquid systems appear to have definite superiority over solid rockets. The characteristic of prime importance for these applications is operability over a very wide temperature range with reproducible ballistics. This is relatively easy to achieve with liquid rockets but extremely difficult with solids since the solid-propellant burning rate varies with the grain temperature. This requirement insures continuing support of exploratory development of small engines powered by storable liquids.

The above review suggests the following areas for research and development on liquid systems:

1. Studies of storable systems of improved I_{sp} and density for use in airborne missiles;
2. Continuing study of combustion instability to provide a more fundamental understanding of the factors important in its onset and build-up. This should provide better criteria for injector design. Otherwise problems that are solved for present sizes and operating pressures may reappear with future higher-thrust systems.

Hybrid Rockets

Hybrid rockets, which use a solid oxidizer and

[‡] Titan II was used to launch the manned Gemini spacecraft on Mar. 23 and Aug. 21, 1965.

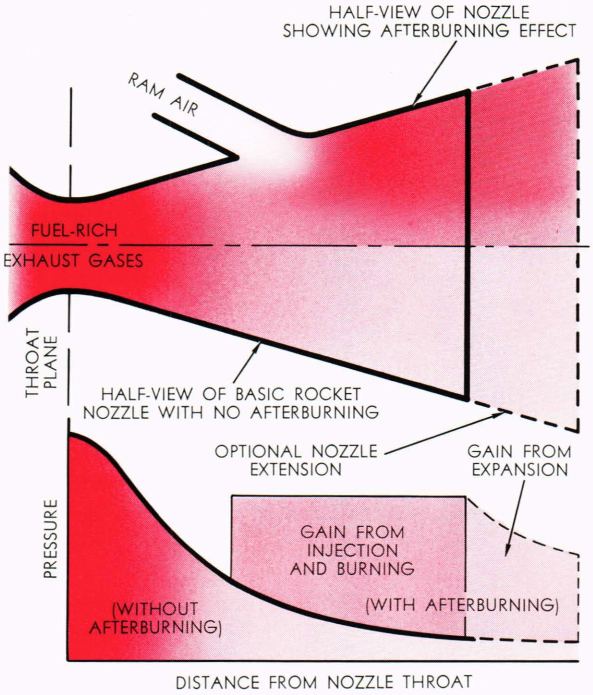

Fig. 3—Schematic of thrust augmentation by afterburning with air. (This material was originally published in *Astronautics and Aeronautics*, Ref. 4.)

liquid fuel or vice versa, were first demonstrated to be feasible approximately ten years ago.[3] However, they were allowed to languish until 1962, when a new generation of rocket engineers suddenly became interested in them. In principle they offer a means of combining the controllability and high performance of storable liquid engines with the high volume impulse of solids. They should be safer than either system and be intermediate in complexity. Unfortunately, there is also a basic drawback that will be difficult to avoid. This arises from the fact that the burning occurs in a turbulent diffusion zone between the solid surface and the mixture of fluid propellant and gaseous combustion products. The dimensions of this zone change as the solid phase is consumed, leading to a change in internal ballistics with time that must be compensated in some fashion by the fluid flow if uniform performance is to be achieved. The rate of consumption of the solid phase is controlled by the mass flux in the channel, and this leads to difficulty in achieving linear burning rates above 0.1 in./sec. It is also necessary to provide volume downstream of the solid component to permit mixing and combustion of the last portions of the solid ejected into the gas phase. These constraints appear likely to restrict severely the usefulness of hybrid systems.

During the past two years an intensive effort sponsored by all of the services has yielded outstanding progress in the hybrid field. A delivered I_{sp} greater than that of the best current solids has been demonstrated with one system. A thorough analysis of the internal ballistics has been made that provides considerable understanding of the combustion phenomena. However, further analysis and demonstration of the complete rocket capabilities will be required before the potential usefulness of these systems can be assessed.

Air Augmentation

The discussion in the preceding sections has brought out a fact that has become increasingly evident in recent rocket planning meetings; namely, the recognition that it has been getting more and more expensive to get less and less gains in rocket performance. It is thus questionable whether future rocket progress will be commensurate with the additional development cost. Attention has therefore focused recently on a re-examination of the potential gains achieveable by air augmentation, which involves injection and combustion of ambient air ducted into the fuel-rich rocket exhaust (Fig. 3). The first stage of most rocket trajectories is completed below altitudes in the neighborhood of 100,000 ft, where ample air exists to give sizable improvement in first-stage impulse if efficient air induction and combustion can be accomplished. Theoretical studies, confirmed by experimental work that draws on experience gained in hypersonic ramjet research, have shown that high efficiency can be achieved, in fact, with sophisticated air induction and mixing design. As shown in Fig. 4, performance corresponding to rocket I_{sp}

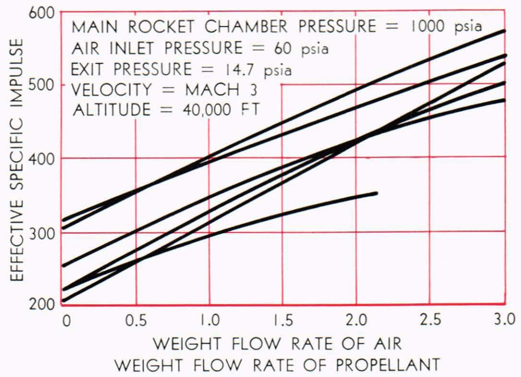

Fig. 4—Performance of various solid propellant formulations with thrust augmentation (see Ref. 4).

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[3] Patent No. 3,136,119 for *Fluid-Solid Propulsion Unit and Method of Producing Gaseous Propellant,* filed in Sept. 1952, was issued to Dr. Avery (assigned to Research Corporation) on June 9, 1964.

above 500 sec appears feasible at booster speeds in the Mach 3 to 4 region. Over the boost trajectory, increase in weight of vehicle payload equivalent to 25 to 50% appears possible in volume-limited systems, including weight of hardware and loss of propellant volume associated with capture, ducting, and mixing of the ambient air. Since work in this field has only recently begun to produce useful data, it is too early to assess the role that thrust augmentation may play in future rocket systems. However, the potential appears definitely greater than for conventional rocket improvement. Stimulating problems for investigation include:

1. Overall system analysis;
2. Air induction design for efficient air induction and mixing;
3. Propellant development to provide maximum overall performance; and
4. Design of inlet hardware for minimum weight and complexity.

Hypersonic Airbreathing Propulsion

Air-augmented rockets, as noted above, promise a major performance gain over conventional types, but they fall far short of the I_{sp} attainable by complete airbreathing systems. This is because airbreathing vehicles carry only the fuel while rockets must carry the oxidizer as well. Since the fuel mass flow rate is a small fraction of the total mass flow rate, the thrust produced per pound of fuel carried in the vehicle can have values as high as 4000 sec for turbojet engines burning kerosene at Mach 2 and approximately 1500 sec for ramjets at Mach 4. As airspeed increases, the I_{sp} of these systems decreases. Turbojets are impractical above Mach 3, which explains why they are not dealt with here, and conventional ramjets burning hydrocarbon fuels have no useful thrust above about Mach 10.[4]

There are, of course, many problems to be solved before these engines become available for Navy applications. A primary difficulty is lack of experimental data that can be used for firm engineering design. Nevertheless, significant progress has been made that supports the feasibility of high speed flight with engines using supersonic combustion.

Work during the past two years has demonstrated that combustion efficiency above 90% can be achieved in supersonic combustion conditions corresponding to Mach 5 flight. Even better efficiency is to be expected at higher speeds. Data obtained at Mach 7 support the analytical studies and give a basis for optimism that inlet efficiency problems will not be severe. The most difficult problems that still await solution are:

1. Design of the leading-edge structures to provide adequate stability in the extreme temperature environment of hypersonic flight. Available materials without cooling are limited to temperatures not much above 3000°F because coatings have not been devised that will prevent oxidation above this temperature. Tungsten alloys would have adequate tensile strength if they could be protected. Otherwise, practical cooling techniques must be developed.
2. Thermal insulation that can be used to protect the structures exposed to high temperatures must be developed. Pyrolytic graphite or pyrolytic boron nitride appear well suited to this use if means can be found to slow surface oxidation, if methods can be developed to attach the insulation to the structure, and if the present cost of these materials can be significantly reduced.
3. Extensive system analyses must be performed to define the detailed requirements of airframe configuration, structures, controls, and propulsion, and to determine the tradeoffs necessary for best overall vehicle performance.
4. Facilities must be developed to meet testing needs of larger scale models in the hypersonic regime. Above Mach 10 new techniques will be required.
5. Flight demonstration of a supersonic combustion ramjet is a must to demonstrate that such engines can indeed fly.

Hypersonic ramjet propulsion would be a particularly fruitful field for American industry to devote its manifold talents to exploring. The payoff will be not only improved national defense but also reduced time and cost for terrestrial intercontinental flight and great savings in cost and convenience for orbital missions.

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[4] W. H. Avery and G. L. Dugger, "Hypersonic Airbreathing Propulsion," *Astronautics and Aeronautics*, 2, June 1964, 42-47.