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A SURVEY OF HYPERSONIC-RAMJET CONCEPTS

by

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A SURVEY OF HYPERSONIC-RAMJET CONCEPTS

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ABSTRACT

A brief discussion is presented of the major problem areas involved in the development of a hypersonic ramjet engine. Keeping the structural temperature to an acceptably low level is the severest problem expected. A rapid survey is made of some of the relatively unconventional concepts that may find application in the hypersonic region. These include supersonic combustors, underwing burning, atmospheric-recombination, engine installation, nuclear power, variable geometry, and fuel-rich operation.

INTRODUCTION

The history of ramjet engines and their place in the family of air-breathing propulsion systems has been a frustrating one - at least from the viewpoint of the ramjet enthusiast. The theory of the engine is old in terms of airplane progress, dating back at least as far as 1906. However, in the intervening years, as the name of the engine changed from Lorin tube, to athodyd, to ramjet, we can point to thousands of reports and experiments but to very few significant applications.

Without spending time in sterile explanations of why this is so, we can more profitably look ahead in anticipation to a new regime of flight where only the ramjet will serve - that is, flight in the atmosphere at hypersonic speeds (defined here as Mach 5 and above). Provided there is sufficient need for such operation, we can now reasonably undertake the development of hypersonic vehicles as a result of advances in the technology of boosters, metallurgy, aerodynamics and structures, engine components, and fuels.

The present paper will be restricted as far as possible to consideration of only the engine proper. Also, since many other papers have covered the general feature of hypersonic ramjets, the present paper will first mention briefly the major developmental problem areas and will then go on to a presentation of several rather unconventional ideas that might be applied to hypersonic ramjets.

As a preliminary, let us first justify our interest in hypersonic flight by reference to figure 1. If the airframe efficiencies (i.e., lift-drag ratio and fuel-to-gross weight ratio) do not change, airplane range is directly proportional to over-all engine efficiency. On this basis, ramjet performance continues to improve well into the hypersonic region, with efficiencies nearly twice as good as that of the common reciprocating engine (about 30 percent). For both long- and short-range missions, light engines are always desirable. Here too, the ramjet is seen to be quite adequate for hypersonic flight as measured by the ratio of thrust-to-frontal area.

What technical problems will confront the engine designer who wishes to take advantage of this good performance potential?

PROBLEM AREAS

A successful hypersonic-ramjet design must prevail against a series of major obstacles. These problems are present to some extent even at more moderate speeds, but their difficulty of solution increases by orders of magnitude in the hypersonic region.

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Structure. - It is futile to talk about hypersonic flight unless we are assured that the engine (and airframe) will preserve their proper geometrical relationships, i.e., will not fall apart before completing the mission. The problem, of course, is that of excessive temperature. For example, the stagnation temperature at Mach 8 is about 4500° F (nearly half the temperature of the surface of the sun). Neither stainless steel nor currently available better materials (such as molybdenum or ceramics) retain adequate strength when exposed to such temperatures. Fortunately, however, design techniques are available to limit the structural temperature to values that can be withstood by practical materials.

The steady-state temperature reached by each part of the structure is a result of a balance between the heat flow into the material and the heat removed from the material. Efforts to secure low temperatures thus involve (1) limiting, as much as possible, the heat transmission from the hot gases to the metal surfaces, and (2) rejecting the heat in the metal to some other sink as rapidly as possible.

The only two practical heat sinks available are the fuel (which means regenerative cooling) and space (which means cooling by thermal radiation).

Regenerative cooling is a well-proven and accepted technique for rocket motors. It is more difficult to apply to ramjet engines because of the lower fuel flow and the more extended surfaces that need cooling. The range of applicability of regenerative cooling is strongly affected by the fuel type. The significant factors are the required flow rate to achieve the desired combustion temperature and the amount of heat the fuel can absorb before reaching its maximum allowable temperature (as fixed for example, by excessive decomposition). Note that high heating value in itself is not a desirable attribute from the cooling standpoint, as this tends to reduce the fuel flow rate.

Figure 2 illustrates the typical variation of regenerative effectiveness at different flight Mach numbers. The fuel is liquefied methane; no cooling is assumed necessary at Mach 4, and only regenerative cooling is utilized at higher speeds. The particular values shown are not of significance; the figure is intended merely to demonstrate that, at sufficiently high speeds, the fuel heat sink capacity is inadequate to completely cool the engine. Still higher flight speeds are feasible, however, if use is also made of radiation cooling, with the fuel employed principally to cool local hot spots such as the nozzle throat.

The successful use of radiation cooling is largely dependent on the geometrical design of the engine. For example, consider the configuration of figure 3. A net dissipation of thermal energy can be accomplished only if a hot surface "sees" a cooler surface. Yet a hot area on the interior of this engine is generally surrounded by other hot surfaces. The inner walls can be cooled only by first radiating to the cooler outer nacelle which then radiates the heat to space. The nacelle thus acts as a radiation shield and impedes the rejection of heat. At low hypersonic speeds the situation may be tolerable. Under more severe conditions, improvements must be made in a manner limited only by the imagination of the designer. For example, a closed-cycle cooling system might be used to transfer heat to the nacelle by convection. Or, slots might be made in the nacelle to facilitate radiation from the inner wall. Or, the separate nacelle might be eliminated altogether. A careful analysis is required to determine the most feasible design.

Several methods are practicable for restricting the flow of heat into the material and thus easing the job of the cooling mechanism, whether it be regenerative or radiative. The most obvious is the use of insulating coatings over the exposed surfaces. In a typical application, it was calculated that a 0.05-inch coating of zirconia would reduce the average internal wall temperature by about 100°; at the same time, the coating increased the engine weight by 30 to 40 percent. Coatings, therefore, are not a complete solution although they can be very valuable in local areas of high heat flux. A weightless form of insulation can be utilized in the combustor and nozzle. This is simply to separate the hot core of combustion gases from the engine walls by a layer of cooler unburned air. At hypersonic speeds the unburned air is none too cool, but this stratification technique can at least mitigate the problem (although a performance loss is often suffered thereby.)

A different means of restricting the heat flow is afforded by varying the gas pressure. Figure 4 illustrates the well-known fact that low pressures greatly reduce the heat transferred from a gas by convection. Certain gases that may be present in the combustion products also heat the walls by radiation. As indicated in the figure, this heat transfer too is reduced by lowering the pressure. Although this discussion has emphasized the combustor, the engine nacelle is externally heated by the hot boundary layer. Here, too the heat input is diminished by a reduction in air pressure.

These facts suggest that flying at higher altitude should be beneficial, and such is indeed the case for radiation-cooled engines. As an illustration of this, figure 5 presents the equilibrium temperature of the nacelle at various altitudes for flight at Mach 7. For simplicity, only aerodynamic heating was considered, under the unrealistic assumption that the hot engine interior does not affect the nacelle temperature. As the altitude is raised, the heat transfer from the boundary layer to the skin decreases due to the lower pressure (despite the adverse rise in ambient, and hence boundary-layer temperature). The ability of the skin to radiate energy to space is unaffected by pressure, and so the net result of the heat balance is a reduction in wall temperature with increasing altitude.

On the other hand, a very different picture prevails for regeneratively cooled engines. Higher altitudes reduce not only the heat flux out of the gas but also the airflow through the engine. Hence, the fuel flow drops, and there is less heat sink capacity. Figure 6 shows that it is more important to preserve a high fuel flow than to decrease the heat flux, so that low altitudes are desirable in this case.

The best design altitude for an airplane is a complicated compromise between such factors as engine size, lift-drag ratio, wing weight, etc. The preceding discussion suggests that a new and important factor, engine cooling, must also be considered in this compromise.

In summary, it is now believed that the proper combination of high-temperature materials and radiation cooling (supplemented by local regenerative cooling) will permit engine operation at any desired hypersonic speed.

Component performance. - The margin between jet thrust and inlet momentum is so slim in any ramjet that the engine performance is extremely sensitive to changes in any of the characteristics of its components.

As flight speed increases, we are confronted with the dual problems that (1) engine sensitivity to component efficiency increases, and (2) it is more difficult to achieve good component efficiencies.

The inlet diffuser is probably the most difficult component to design because there are so many often-contradictory factors to consider. The kinetic-energy efficiency should be high to minimize fuel consumption. But efficient inlets often suffer from excessive weight or drag. High pressure recovery increases engine thrust and reduces the surface area to be cooled. But high internal pressures increase hoop stresses and cause increased heating rates. Other factors include boundary-layer bleed requirements, starting difficulty, sensitivity to angle of attack, mechanical complexity, flow distortion, off-design operation, etc.

An example of a possible hypersonic diffuser is pictured in figure 7. Features of this inlet are the all-external-compression isentropic spike, the drag-free cylindrical cowl, the throat bleed system, and the absence of a subsonic diffuser. This design theoretically provides kinetic-energy efficiencies of over 90 percent at hypersonic speeds.

The combustor recognizes that it is flying at hypersonic velocities only because of the high inlet-air temperature. The cooling problem thereby created has already been discussed. The high temperature does confer one benefit. Evaporation, diffusion, and kinetic-reaction rates are all increased, making it possible to achieve higher combustion efficiency in a shorter combustor length. On the other hand, with some fuels, the high air temperature may cause the fuel droplets to decompose and form incombustible products before reaching the flame front.

The hypersonic-ramjet nozzle presents no new problems. However, it represents a much larger physical part of the engine than is the case at supersonic speeds. Careful attention must therefore be paid to minimizing its weight and external drag, in addition to achieving efficient expansion. A graphic illustration of this is given in figure 8, which pictures a proposed Mach-7 design. At first glance, the nozzle comprises practically the whole engine.

There is one vital component problem not yet mentioned, for which responsibility can be charged to both the combustor and the nozzle. Although perhaps it would be fairer to place the blame on the basic thermodynamic cycle. At low temperatures, when heat is added to a gas, it acts to increase the translational energy of the molecules. When passed through a nozzle, the translational motion of the molecules produces a pressure force on the walls which gives us a thrust. At high temperatures, however, some of the added energy is absorbed by chemical dissociation and some by vibration and rotation of the molecules. As the gas expands through the nozzle there is a tendency for these other forms of energy to be converted into translational energy, which is the only form capable of producing thrust. However, if the expansion process is carried out too rapidly, this readjustment does not have time to occur; this is particularly true for the energy tied up in dissociation. The magnitude of the loss due to failure to regain the dissociation energy is shown in figure 9. There will always be some recombination during the expansion process so that an actual engine will fall somewhere between these two curves. But if the frozen case is a reasonable approximation, the engine will develop less than 50 percent of its potential at high speeds. Unfortunately little is now known about what conditions will prevail in a hypersonic-ramjet nozzle.

Since dissociation is a function of gas pressure, this may be another factor to consider when selecting the airplane design altitude.

UNCONVENTIONAL CONCEPTS

Many variations or modifications of the ramjet cycle and its components are possible, several of which are described in this section. Some of these ideas are quite old; they are unconventional only in the sense that they are not now in common practice. Others can at best be considered speculative and subject to disproof by further study. To reiterate a previous point - it is vital to evaluate all such proposals in the light of how they may affect the cooling problem.

Internal supersonic combustion. - It is an interesting fact of fluid mechanics that the addition of heat to a supersonic-gas stream decelerates the flow and raises its static pressure. Since these are the functions performed by an inlet diffuser, the possibility is suggested of eliminating the diffuser and combining the compression and heat-addition processes in a combustor having a supersonic inlet velocity. Such an engine might look like that of figure 10. A number of advantages might accrue from this device: (a) eliminating the diffuser lightens the engine, (b) with supersonic velocities, the static temperature and pressure are lower, reducing the heat load to the walls, both convective and radiative, (c) the lower pressure permits thinner, lighter combustor walls, (d) the lower temperature reduces dissociation, minimizing the possible losses due to frozen expansion.

Of course, adding heat in a fast-moving gas incurs a large momentum-pressure drop. The comparative performance of the supersonic-combustion engine with the conventional ramjet depends on whether this pressure drop is larger or smaller than the ordinary diffuser and combustor pressure drop. A comparison of over-all engine efficiency is shown in figure 11 (from ref. 1). Values are given in all cases relative to a conventional ramjet that has a two-cone inlet.

The supersonic engine with a Pitot inlet has a combustor velocity equal to the flight speed. Performance in this case is poor for the flight speeds illustrated. Calculations show that better results can be obtained by utilizing some initial diffusion, while still maintaining a supersonic combustor-inlet velocity. Thus an engine with a wedge-type inlet is improved to the extent that it exceeds the conventional-engine performance at Mach numbers above 7. The so-called "isentropic" inlet is often applied to conventional ramjets but, of course, it still has appreciable losses. There is some hope that, for an inlet which only partly diffuses the air without passing through the sonic point, truly isentropic deceleration can be approached. If this is the case, then even better supersonic-combustion performance is possible, as shown. (Of course, these comparisons depend on the level of performance assumed for the conventional ramjet.)

Whether these analytically predicted efficiency gains can be realized in practice is still subject to experimental confirmation. The problems of securing stable, efficient supersonic burning are formidable. All that can be said now is that many organizations are interested and are working in the field, but the answers are not yet available.

External burning. - The principle of the supersonic-combustion ramjet can be carried one step further by eliminating the engine entirely. Instead,

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fuel is added and burned in the free air flowing in the vicinity of the airplane. This is illustrated in figure 12, where heat is being added under a triangular airfoil moving to the left. The pressure field from the combustion zone impinges on the rear edge of the wing, with both vertical and horizontal components. The lift force can be used either to reduce the wing area or to raise the airplane ceiling. The forward component of the pressure force yields a large enough thrust to propell the airplane.

The fuel can most easily be added and burned in a small concentrated area next to the wing. However, calculations show that it is more efficient to burn the fuel in a distributed flame front as shown in the figure. The pressure fields from each infinitesimal part of the combustion sheet propagate up to the wing along Mach angles and reinforce each other. How this sheet of combustion can be established with a real airplane is not known.

Some rough estimates of comparative airplane performance are shown in figure 13 (from ref. 2). Range is given relative to the Mach-6 underwing-burning case. The calculations were too crude to warrant emphasizing the quantitative results. Nevertheless they do indicate that underwing burning may offer improved hypersonic range over the conventional ramjet.

Apart from the range criterion, there are other advantages to be claimed for underwing burning: No engine is required, thereby making a substantial weight saving. The combustion causes no severe cooling problem: in the distributed case, the hot gases do not contact the skin; in both cases, the skin is free to radiate directly to space. The airplane can be operated over a wide range of flight speeds without the handicap of engine off-design problems. By spreading the flame over a wide area, the local temperature rise can be kept low, minimizing the deleterious effects of dissociation.

Even if detailed studies should prove that underwing burning is impractical for cruising operation, it may still be useful as a secondary propulsion device. At the cost of some extra fuel injectors, the airplane can be given the capability in cases of emergency to fly faster or higher or to have greater maneuverability.

<u>Solar-powered ramjet</u>. - A small part of the solar energy falling upon the earth is absorbed by the atmosphere in various chemical forms. The principal storage mechanisms are the formation of ozone and the dissociation of oxygen and nitrogen. The solar energy potentially regainable from a pound of air in these states is appreciable, in some cases more than could be obtained by the stoichiometric combustion of chemical fuels. In consequence, numerous proposals have been made to utilize this stored energy in a ramjet and so eliminate the need for fuel.

The great obstacle to such schemes is that the storage effects occur only at high altitudes where the atmospheric density is extremely low. The airflow through an engine, and hence the thrust, are thus very limited.

The characteristics of the earth's atmosphere at high altitudes have not yet been fully determined. One of the more optimistic (for this purpose) atmospheric models was used for the calculation presented in figure 14, which shows the thrust developed by an ideal engine (100-percent overall efficiency) that completely utilizes all the stored energy. All values are very low, with the maximum occurring at an altitude of about 300,000 feet. This thrust results from the recombination of oxygen, which

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at this altitude is entirely in the atomic state.

The thrust developed by a real engine will depend both on the internal pressure losses which may be present and on the extent to which recombination approaches the equilibrium condition. The latter factor depends on the chemical kinetics of the recombination process, which are not adequately known at the present time. Charwat (ref. 3) calculated that the optimum Mach number for the recombination ramjet is in the region of only 2. At this speed he estimated that an engine constructed entirely of 1-mil Mylar plastic would have to have a 90-foot diameter to support just its own weight. Payload capacity is therefore very small, even for extremely large engines.

Using different assumptions, Baldwin and Blackshear (ref. 4) concluded that the engine is not suitable for any mission requiring aerodynamic lift but that there may be a marginal use as a sustainer for a low-altitude satellite. Their analysis is of particular interest here because it utilized the same "supersonic-combustion" principle described earlier.

Engine installation. - By properly combining the engine with the airframe, significant performance gains can be achieved. Furthermore, these gains are usually greater at higher flight speeds and so become important in the hypersonic region.

One group of benefits accrues from proper placement of the inlet. Locating the inlet behind an oblique shock generated by the airframe (e.g., by either the fuselage or the wing) provides an additional degree of compression and generally improves the inlet pressure recovery. In addition, the pressure drag and the induced drag of the vehicle lower the momentum of the air stream. Since the net engine thrust is equal to the exit minus the inlet momentum, utilizing the low-momentum air in the engine results in an increase in thrust and efficiency. At Mach 5, these two effects are estimated to yield range increases in the order of 20 percent.

A more extreme use of this low-momentum principle lies in placing the engine inlet within the boundary layer. (This same principle has also been proposed for such diverse applications as submarines and lighter-then-air ships.) At Mach 5, this may yield 15-percent greater range. However, this estimate ignores the practical problems involved in trying to utilize boundary-layer air within the engine. For example, the inlet pressure recovery would probably suffer.

Range increases can also be achieved by canting the exit jet downward in order to obtain lift. Appreciable lift can be developed with little loss in thrust; thus the wing need not support as much weight and can either be made smaller or operated at a lower angle of attack. In either case the drag due to lift is reduced, and so less propulsive power is needed from the engine. The estimated range increase from this device is shown in figure 15, using the optimum angle of cant at each point. The improvements are greatest for the least efficient wing but are worthwhile even for a lift-drag ratio of 8.

Nuclear power. - Most applications of nuclear power to aircraft propulsion propose that a reactor be used to heat the working fluid, either directly or through an intermediate fluid. The fluid must thus be at a lower temperature than the reactor walls in order to transfer heat. Such a system does not possess hypersonic capability, as the inlet-air temperature already is as high or higher than the maximum allowable wall temperature for current materials.

An indirect approach is possible, however, which avoids this temperature difficulty. In this case the nuclear power source is utilized to generate electrical energy. A closed cycle of some sort is employed in order to avoid contact with the hot engine airflow. The generated power is then used to heat the air to any desired temperature by discharging an electrical arc across the "combustion chamber." The temperature limitations of the power source are thus dissociated from the heat-addition process.

A conventional power-generating system (e.g., reactor plus turbogenerator) is much too heavy for airplane applications. Instead, Kaeppeler (ref. 5) has suggested using atomic batteries for this purpose. Their operation is indicated in figure 16. Plates are constructed of a radioactive material that emits β-particles, i.e., electrons. The electrons fall upon a nearby electrode, which thereby becomes negatively charged; the radioactive plate now has a deficiency of electrons and so is positively charged. The flow of electrons across the separating gap will continue until the kinetic energy of the β particles is insufficient to overcome the potential difference that has been built up. Quite large potentials can be achieved in this manner, in the order of many thousands of volts. To obtain any appreciable steady-state current, large numbers of plates must be connected in parallel.

Kaeppeler estimated the total weight of such a generating system for various materials; his data are shown in figure 17, after converting to English units. The sloping lines demonstrate that, if other properties (molecular weight, energy per disintegration) remain constant, the trick in obtaining light-weight β-decay batteries is to use substances

with very short half-lives. Such materials emit their β-particles in a short period of time and so produce high currents. The best material shown is an isotope of copper having an atomic weight of 67 and a half life of only 3 days. A one-pound battery of this material would generate 10,000 horsepower of electrical power. As an example of what this means, a Mach-10 ramjet-powered airplane is calculated to require Cu^{67}-batteries weighing 1/100 of 1 percent of the airplane gross weight. This entirely replaces the otherwise necessary chemical fuel that might weigh 50 percent of the gross weight. Also, the airplane range is now limited only by the useful lifetime of the batteries.

Several disadvantages to this scheme are apparent: (1) The short life-time implies that means of artificially producing the copper isotope (and the complete battery) must be available near the launching site. Cu^{67} cannot be produced by neutron bombardment, as in a reactor. Instead it is necessary to use a large and expensive device such as a linear accelerator or a cyclotron. (2) The isotope emits gamma rays in addition to the β-particles, hence some shielding is needed. (3) Kaeppeler's data presume the availability of pure radioactive material. Actually the isotope concentration is likely to be quite low. (4) According to some authorities the weight of the non-radioactive components of the battery is apt to be considerably higher than Kaeppeler assumed. Similar remarks would apply in varying degrees to the other radioactive isotopes.

Despite these discouraging comments, the magnitude of the possible benefits of β-decay batteries is so great that more extensive study in this direction seems warranted.

Self-acceleration. - Due to its lack of low-speed thrust, the ramjet vehicle must rely upon some other propulsion system to boost it to its effective operating range. Normally rockets are used for this purpose. The required rockets for boosting to hypersonic speeds are quite enormous. For example, it is estimated that the booster for a Mach-8 missile will weigh three times as much as the missile.

This fact gives rise to the hope of utilizing the ramjet for at least a portion of this acceleration. However, the fixed-geometry ramjet possesses only very limited self-acceleration capability. Reasonably good acceleration could be obtained if variable-geometry components are employed. In particular, methods are desired to control the diffuser inlet areas and the nozzle throat area.

Due to the hostile thermal environment at high speeds, it will be difficult to develop reliable continuously variable components. An alternative solution for the inlet is to fit an auxiliary low-speed diffuser to the engine (fig. 18). After accelerating through a range of low Mach numbers it would be discarded, exposing the cruising inlet. Wind-tunnel tests have demonstrated that the auxiliary inlet can be so jettisoned.

A more flexible approach can be employed with the exhaust nozzle through use of the afterburner principle (ref. 7). The larger flow area permits addition of much more heat downstream of the primary nozzle. By changing the proportions of fuel burned in the primary and afterburners, the thrust may be varied continuously from the cruise to the peak value.

Fuel-rich operation. - At high flight speeds engine performance tends to become less and less sensitive to variations in fuel-air ratio. For example, figure 19 illustrates the relative ranges of ramjet vehicles when designed for different equivalence ratios. Very little effect is noted in the lean region. It is especially significant that the range losses are not great even in the rich region. At Mach 9, for example, the fuel flow could be 25 percent higher than stoichiometric with only about a 10 percent reduction in range. Thus, if needed for regenerative engine cooling, the stoichiometric fuel-air ratio need not be a limit.

Of course, adding fuel beyond the stoichiometric point does not increase the chemical energy release in the combustor. However, the excess fuel provides thrust due to two other factors: (1) Appreciable kinetic energy is stored in the fuel purely as a result of the high flight speed. For example, at Mach 10, each pound of fuel contains about 2000 Btu of kinetic energy, which, when mixed with the airflow, adds about 140 seconds to the specific impulse. (2) Appreciable thermal energy may be present in the fuel, particularly if it is circulated next to the airplane skin for structural cooling purposes. (The sum of these two energy sources is so great that Moeckel (ref. 6) calculated the specific impulse of a Mach-10 rocket flying in the atmosphere to be 360 seconds, even with no chemical combustion.)

As an extension of this thought Breitweiser and Morris (NASA) have proposed a ramjet design that utilizes extremely high equivalence ratios to reduce the thrust loss encountered by the conventional ramjet at Mach numbers in the order of 10 and above. Their design overcomes several of the major obstacles to using ramjets at very high speeds: (1) by varying the amount of fuel added, the inlet and nozzle areas can be matched over the entire range of flight speeds with no variable-geometry components,

(2) the high fuel flows can be used to cool not only the engine but also the airframe if necessary, and (3) the rich mixture keeps the combustion temperature so low that dissociation does not take place, and so there can be no loss due to frozen nozzle expansion. Preliminary studies indicate that a fixed-geometry engine of this type can accelerate with good thrust margins all the way from supersonic speeds up to Mach 18 or 20, with a better specific impulse than a rocket.

CONCLUDING REMARKS

In recent years major progress has been made in the areas of airframe aerodynamics and engine fuels and components. As a result, hypersonic-ramjet vehicles appear to be practical load-carrying devices. The developmental probelms of the engine are formidable, but solutions can be seen. Further improvements in vehicle performance may result by applying various "unconventional" concepts to the engine.

We are now capable of predicting with reasonable assurance the expected performance of hypersonic vehicles. Such information makes it possible to weigh the comparative merits of ramjets and competing propulsion systems and to rationally decide whether the expense of developing hypersonic-ramjet vehicles is worthwhile.

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HYPERSONIC RAMJET PERFORMANCE

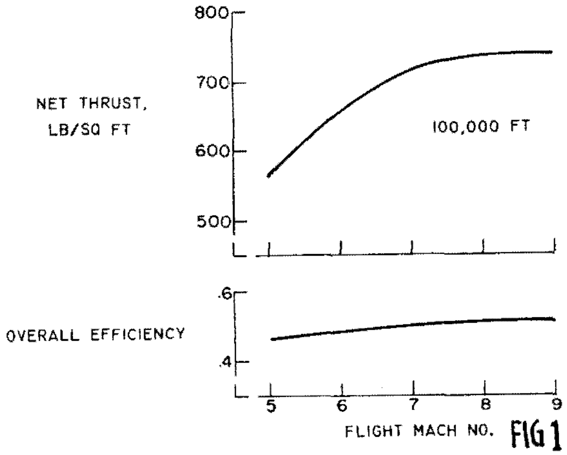

FIG 1

FUEL AS COOLANT

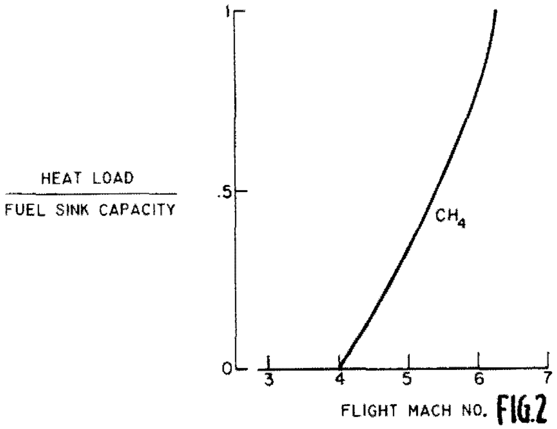

FIG.2

TYPICAL ENGINE CONFIGURATION

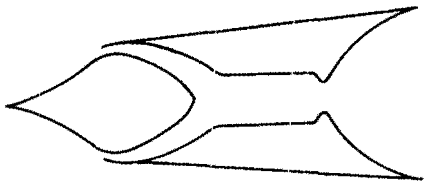

Fig. 3

LOWER PRESSURE REDUCES HEAT TRANSFER FROM GASES

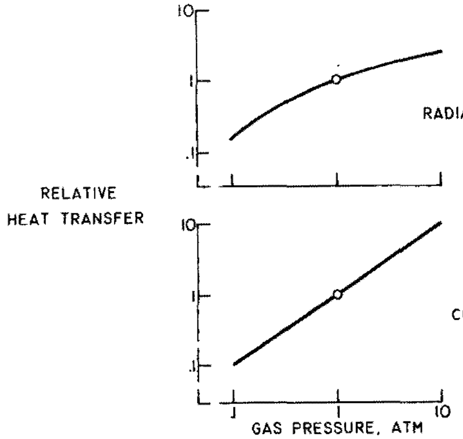

FIG.4

RADIATION COOLING IS EFFECTIVE AT HIGH ALTITUDES

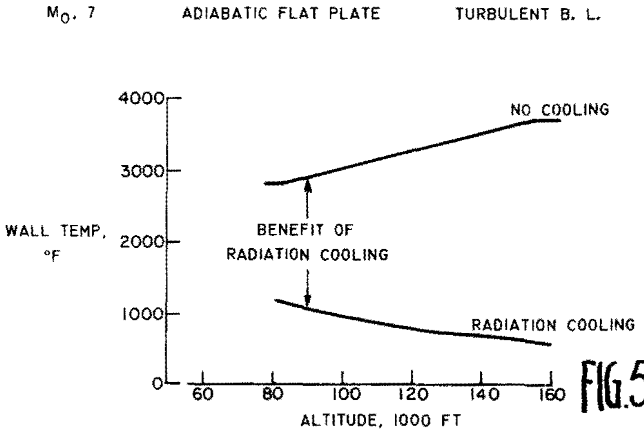

FIG.5

HIGHER ALTITUDE REDUCES REGENERATIVE COOLING CAPACITY

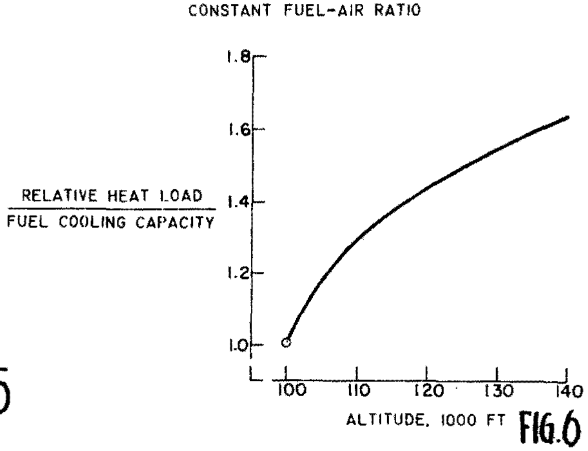

FIG.6

HYPERSONIC INLET

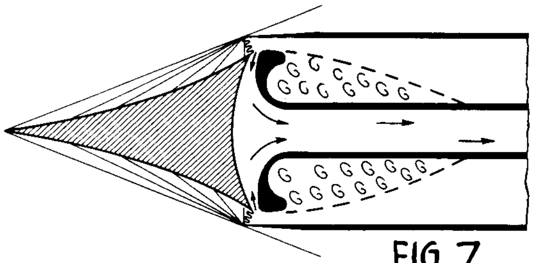

FIG. 7

RAMJET ENGINE

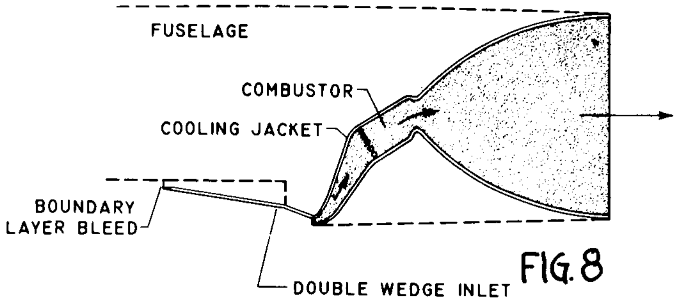

FIG. 8

DISSOCIATION MAY HURT EFFICIENCY

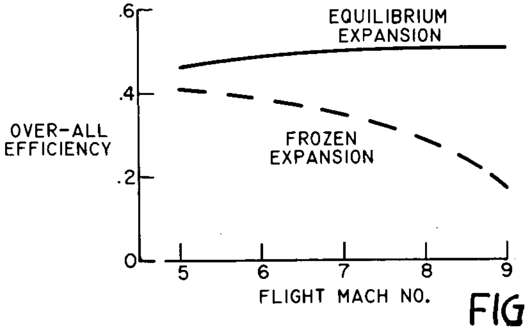

FIG. 9

SUPERSONIC-COMBUSTION RAMJET

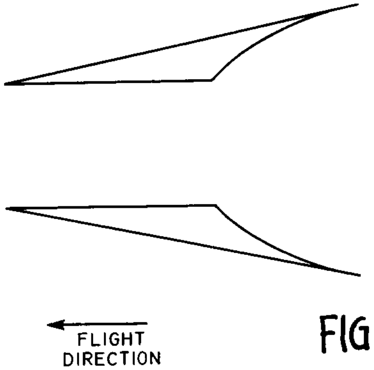

FIG. 10

SUPERSONIC-COMBUSTION RAMJET PERFORMANCE

(RELATIVE TO CONVENTIONAL ENGINE WITH 2-CONE INLET)

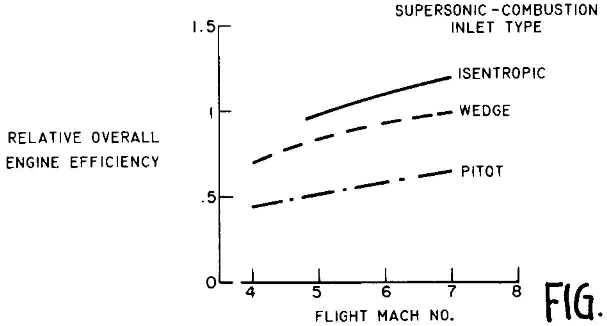

FIG. 11

THRUST FROM UNDERWING BURNING

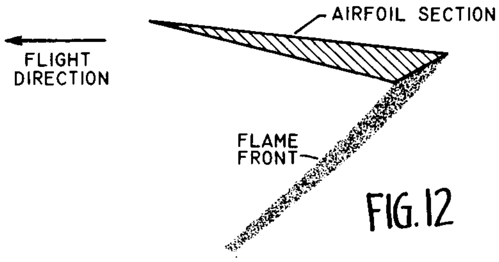

FIG. 12

12 WEBER

AIRPLANE PERFORMANCE WITH UNDERWING BURNING

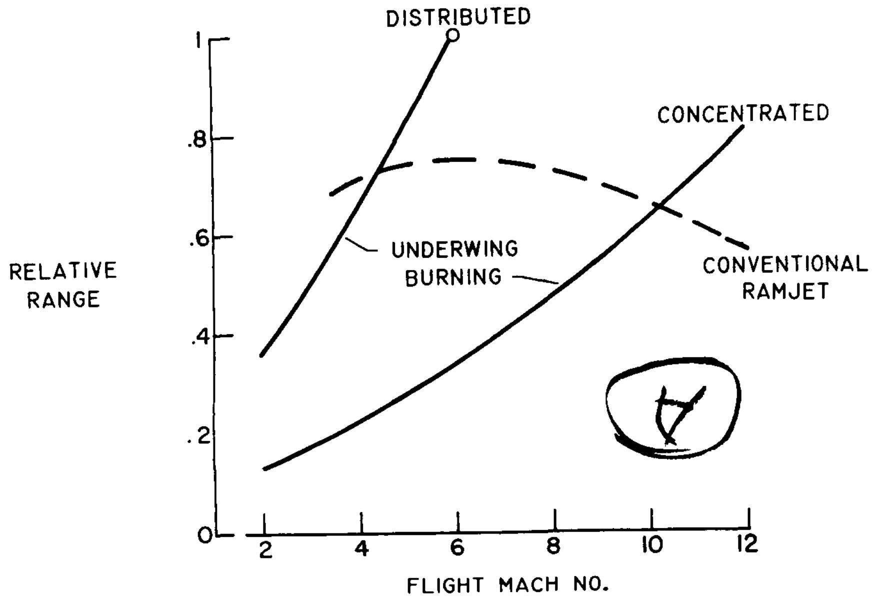

Fig. 13

AVAILABLE THRUST FROM ATMOSPHERIC ENERGY

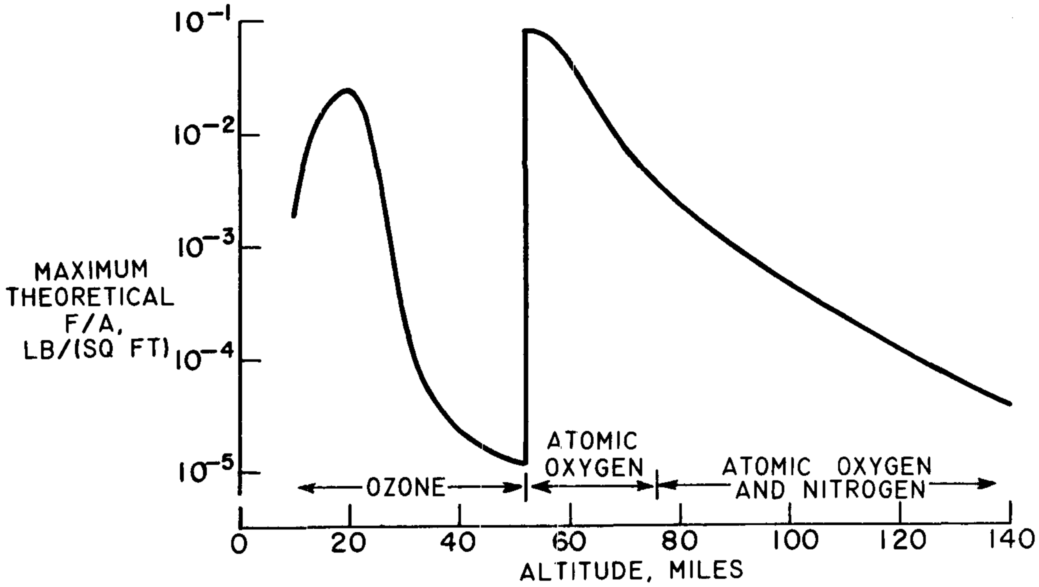

Fig. 14

BENEFITS OF EXHAUST-JET CANT

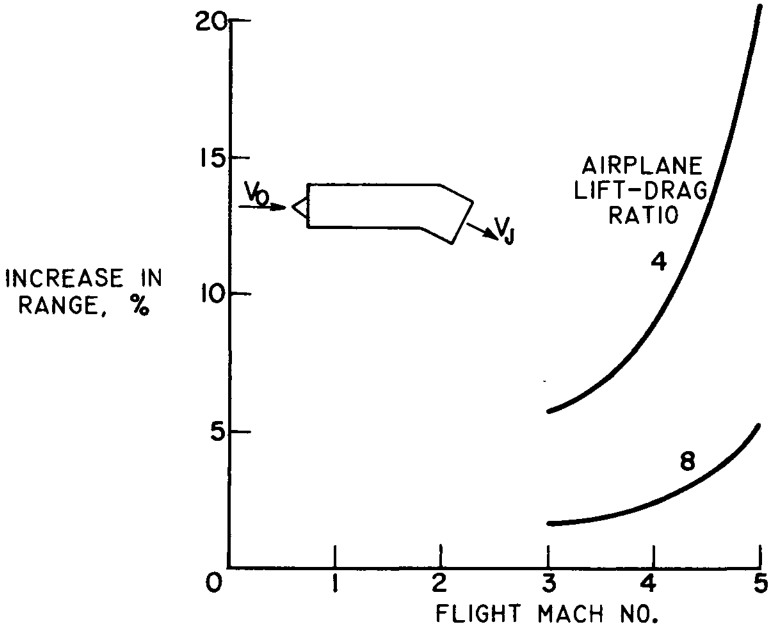

Fig. 15

β-DECAY BATTERY

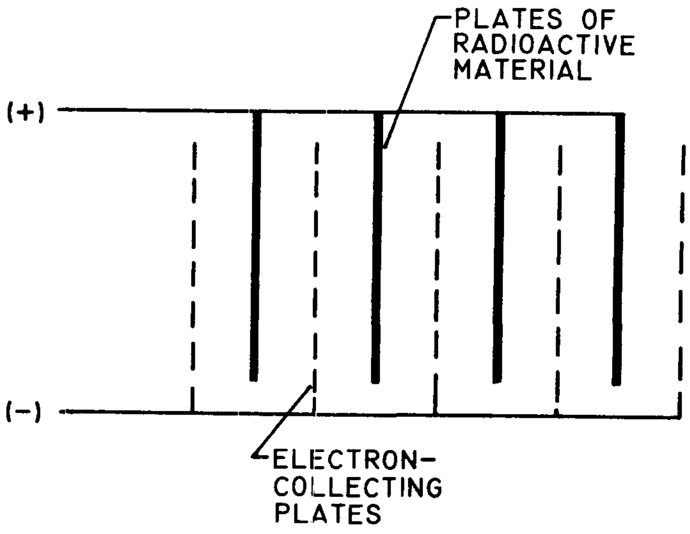

Fig. 16

·13·WEBER

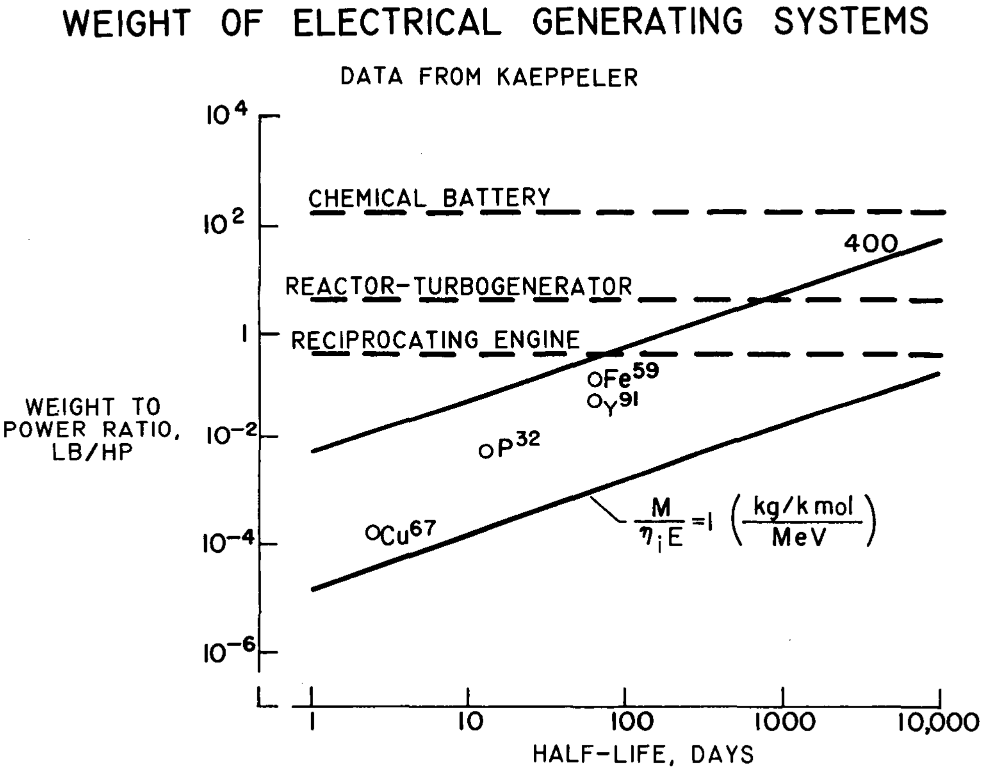

Fig. 17

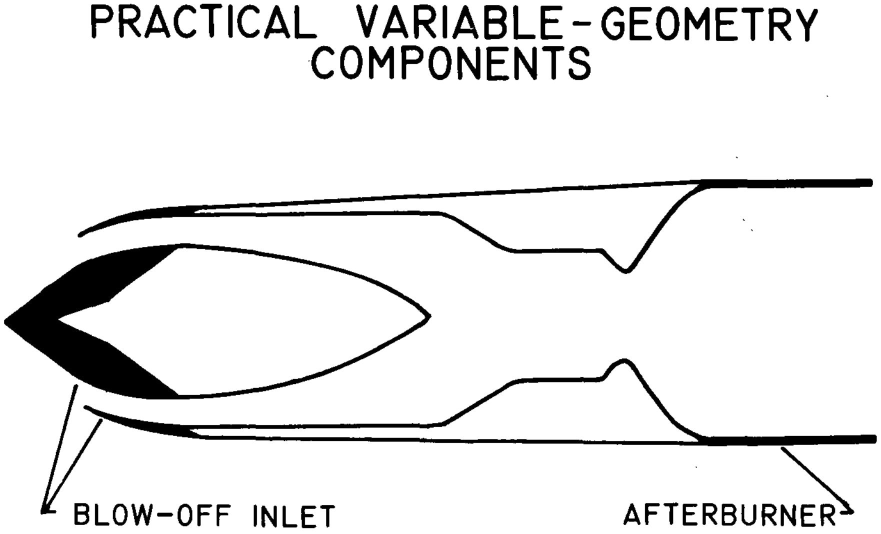

Fig. 18

14. WEBER

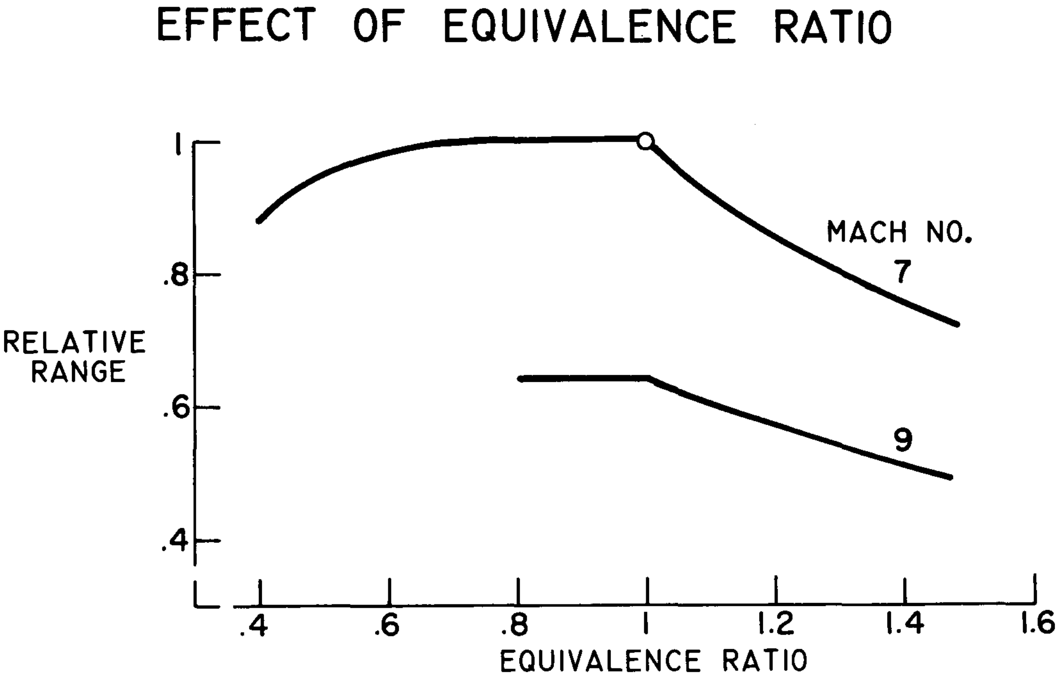

Fig. 19

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