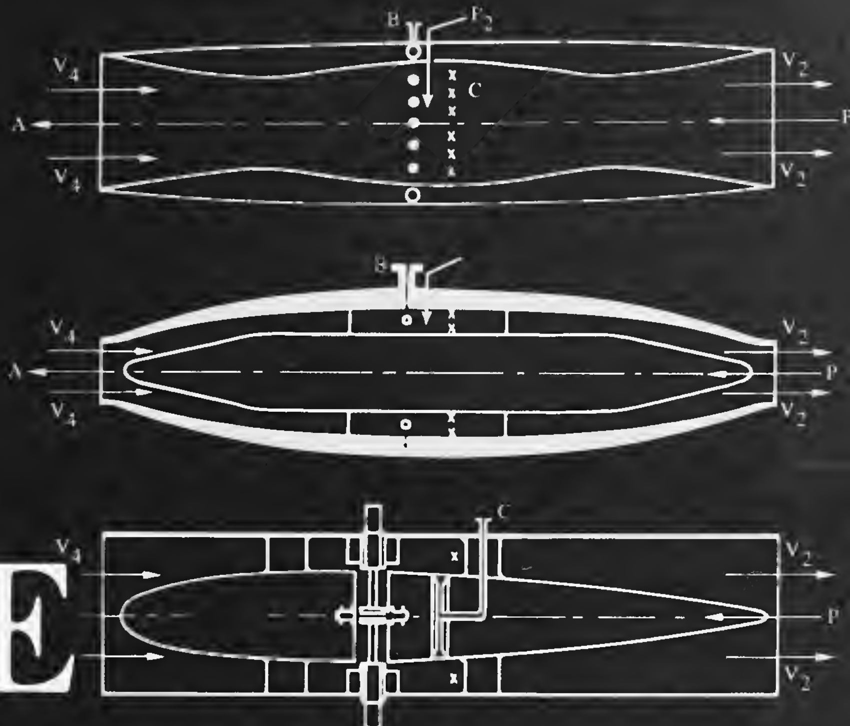

THE POCKET RAMJET READER

CHEMICAL SYSTEMS DIVISION

UNITED TECHNOLOGIES

CSD's Modern Versatile Ramjet Facility Located at Coyote, California

THE POCKET RAMJET READER

Cover Design - Reproduction of the Figure from the German Patent
Issued to Albert Fono in 1928 for a Ramjet Engine

CHEMICAL SYSTEMS DIVISION
UNITED TECHNOLOGIES.

Foreword

High technology disciplines almost always bristle with the specialized jargon peculiar to their field. Although an understanding of the jargon can be obtained from textbooks and treatises, in many cases this may be both difficult and time consuming. It is a purpose of this booklet to provide in one source a basic, simplified explanation of the terms, elements, and operating parameters of ramjet technology. Armed with the basic information contained herein, the reader should be able to participate knowledgeably in discussions, presentations, and other business activities that involve ramjet propulsion systems. He should also be able to use this information as a basis for extending his knowledge of this complex and challenging field with more advanced technical data.

Portions of the material contained herein have been obtained from the following sources:

Twenty-Five Years of Ramjet Development, William H. Avery, Jet Propulsion, Vol. 25, No. 11, November 1955, pp 604-614

Aircraft and Missile Propulsion, Vols. I and II, M. J. Zucrow, John Wiley & Son, Inc., 1958

Aircraft Propulsion, P. J. McMahon, Harper & Row Publishers, Inc., 1971

These references provide excellent treatments of ramjet technology and are recommended to those readers who desire a more detailed and comprehensive understanding of the subject matter.

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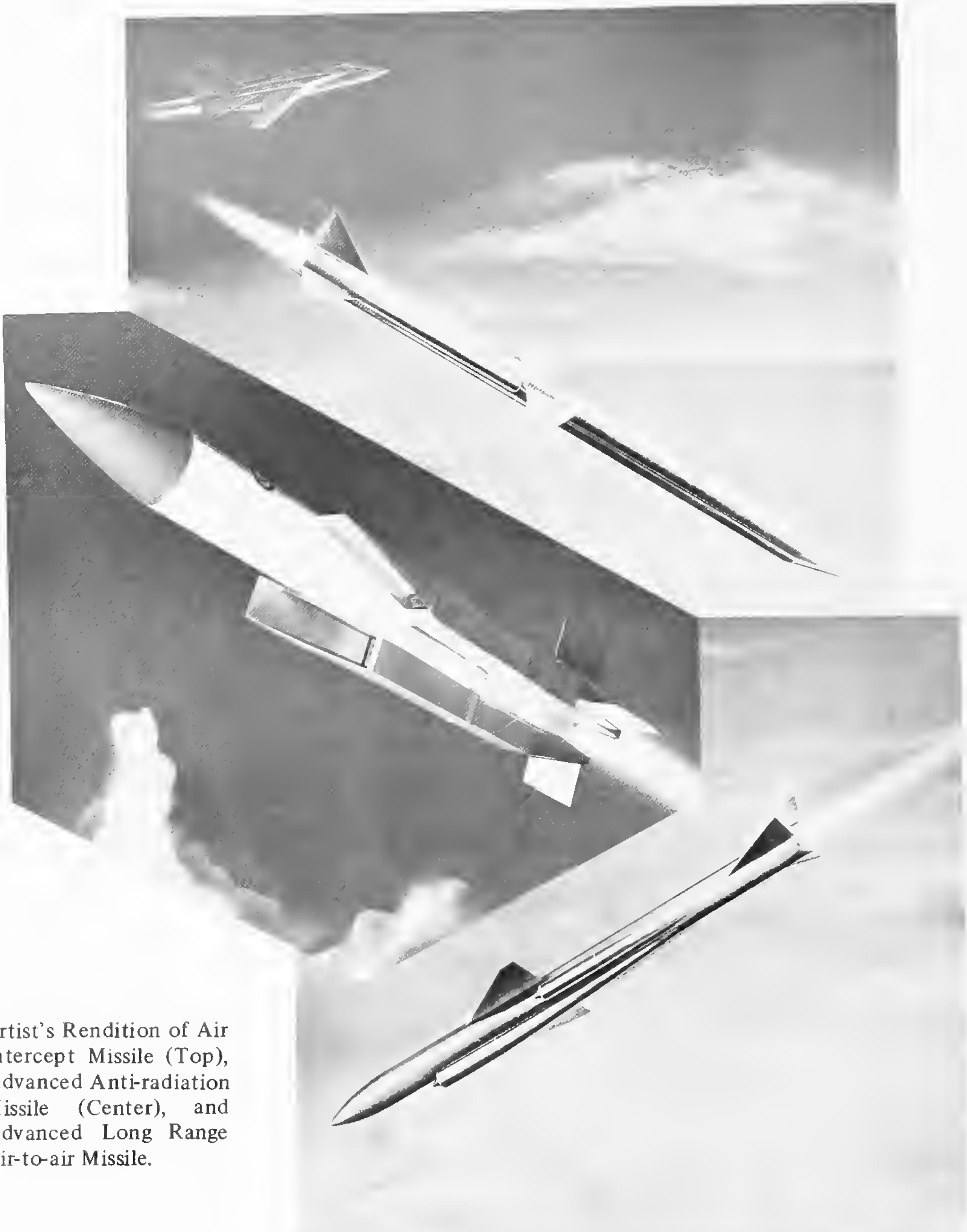


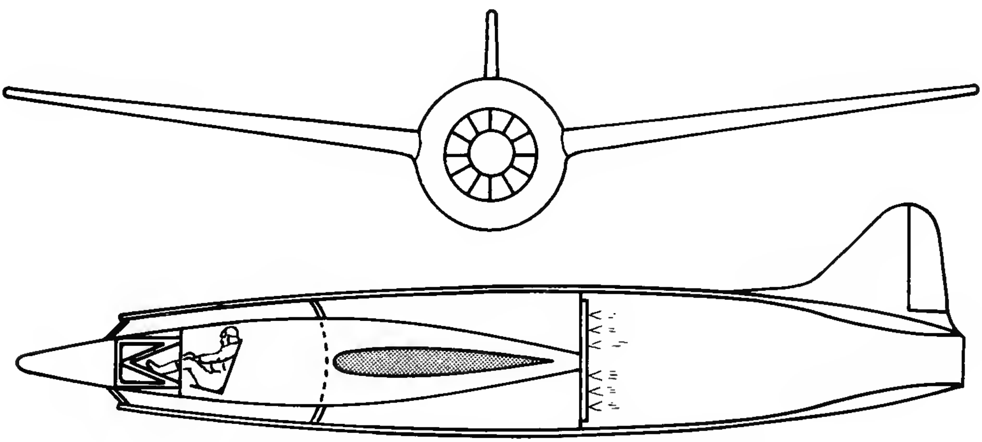
Artist's Rendition of Air Intercept Missile (Top), Advanced Anti-radiation Missile (Center), and Advanced Long Range Air-to-air Missile.

1 Historical Perspective

Origin of the Ramjet

The concept of the ramjet engine is attributed to a Frenchman, Rene Lorin, who first described such a device in 1913. Since he did not envision flight at supersonic speeds, his analysis of ramjet propulsion was based on propelling bodies at subsonic speeds, and he concluded that the ramjet engine would have a low thermal efficiency. A British patent issued in 1926 discloses the application of two ramjet-like devices for propelling artillery shells, but there is no evidence that the devices were ever built. The first patent (German) that disclosed the use of ramjet engine as a propulsion system for supersonic flight was issued to Albert Fono in 1928. Again, there is no evidence that his engine was ever built.

As a result of work begun around 1933, a French patent was issued to Rene Leduc in 1935 on the design of a ramjet-propelled airplane. By 1935 Leduc had tested the thrust of a small unit at speeds up to 679 mph, and the results were so encouraging that the Air Ministry authorized design and construction of a research airplane to be propelled by a ramjet engine. As conceived by Leduc,



Ramjet-propelled Airplane as Conceived by Leduc atmospheric air entered an annular scoop surrounding the cabin, the air temperature was raised by fuel burners located near the midsection of the airplane, and hot gases were discharged at the rear with a large jet velocity. Active work on the airplane was begun in 1938, and during 1939 several engine components were tested over the Mach number range 1.65 to 2.35. The development program was interrupted by World War II, but the experimental airplane was completed and subsonic flight tests were conducted in 1949.

During World War II a great deal of effort was expended on ramjet engine development in Germany, Great Britain, and the United States. The Germans studied the application of the ramjet engine to fighter aircraft, conducted tests of subsonic ramjet engines, and investigated the possibilities of solid fuels and suspensions of metals (such as aluminum in fuel oil). The Germans made extensive studies on supersonic spike-type diffusers; much of this research was in connection with applying ramjets to the propulsion of artillery shells.

British work on the ramjet engine (originally termed the Athodyd, for aerothermodynamic duct) began during World War II but was largely confined to theory. Some experimental work was performed on small engines primarily for missile propulsion.

In the United States the potential of the ramjet engine was first pointed out in 1941, but not until 1944 was serious effort expended on ramjet engines for supersonic propulsion. The first work of consequence began at the Applied Physics Laboratory of Johns Hopkins University under sponsorship of the Navy's Bureau of Ordnance. The first flight tests in 1945, using a 6-inch diameter engine burning heptane, are probably the first experimental demonstration of the acceleration of a ramjet engine in supersonic flight. These early flight experiments were conducted at low altitudes with the most rudimentary fuel controls to maintain maximum thrust output. Consequently, many of the problems associated with flight at high altitude and with flight maneuvers were not encountered. The encouraging results of these low-altitude tests interested the military services in supporting development programs for several ramjet engines to propel supersonic guided missiles. Thus, the Navajo long range missile, the Bomarc interceptor missile, and the Talos missile were designed with ramjet propulsion systems.

The Ramjet Recession

Despite these early systems, some of which progressed into full operational use, interest in ramjets abated, mostly following cancellation of the Navajo strategic missile program in favor of the Atlas ballistic missile. One of the major considerations in choosing Atlas as the nation's first intercontinental missile was that it followed a pure ballistic trajectory after the conclusion of powered flight some six minutes after launch. The Navajo, on the other hand, employed a large liquid rocket booster (almost identical with the engine employed for Atlas) to reach supersonic speed and thereafter had to operate its ramjet engines for several hours to achieve its intended range. For the intercontinental missile, therefore, a ballistic trajectory was preferable. There were also serious technical questions about reliability of the airborne power supply operated by a hot gas turbine, on which success of the mission depended critically.

For nearly two decades interest in ramjets was limited essentially to research; no new ramjet propulsion systems were specified for operational vehicles. Meanwhile, both solid and liquid rockets continued as primary power sources for launch vehicles and tactical missiles, attaining an advanced state of development in the process.

There were two main reasons for the lack of interest in ramjets. First, the earlier, more modest requirements for tactical missiles could be met by solid propulsion systems. Second, even though the airbreathing ramjet offered much higher performance than a rocket with its self-contained source of oxygen, the ramjet had to be boosted to supersonic velocity before it could operate. This requirement made necessary a separate rocket for the boost phase, incurring the increased complexity of two separate propulsion systems.

The Ramjet Resurgence

The recent revival of ramjet propulsion stems from changes both in technology and in tactical missile requirements. The significant technology change was emergence of the integral rocket ramjet, which combines the rocket boost and ramjet sustain functions in one efficient propulsion system.

Tactical missile requirements must be responsive to the international threat environment, which has changed because of the ability to detect launch platforms at longer range. Because of this improved ability, missiles must be launched much further from their targets. They must be capable of longer range and higher speeds at all altitudes and in many cases be under power all the way to the target. To obtain these capabilities in a missile of minimum volume requires the high performance of a low cost airbreathing propulsion system. The IRR fulfills these requirements effectively. Over the next five to 10 years, therefore, IRRs are expected to form one of the major propulsion systems in the nation's arsenal.

Designing and testing IRRs requires a wider range of skills than rockets, and the test facilities need to be much more elaborate. Nevertheless, IRRs offer such advantageous operating characteristics that they are now being specified as propulsion systems for several next-generation vehicles. It seems clear that the day of the ramjet has finally arrived, and that the IRR will become a prominent member of the family of jet propulsion systems during the 1980's.

2 General Characteristics of Ramjets

The ramjet engine is one of the youngest of the family of jet propulsion devices that includes the rocket and the turbojet. Airbreathing ramjets give much higher fuel efficiency than rockets since ramjets use inlet air as a source of oxygen. Self-sufficient rockets, on the other hand, must carry their own oxidizer and bear the consequent weight penalty. Accordingly, although rockets must be chosen for propulsion outside the earth's atmosphere, ramjets generally outperform rockets if there is a ready supply of air.

Because the ramjet depends only on its forward motion at supersonic speeds to effectively compress intake air, the engine itself employs no moving parts. It is therefore capable of a simplicity, lightness of construction, and high flight speed not possible in other air-breathing engines. These features, plus the high thermal efficiency it can achieve, make the ramjet a particularly attractive choice for propelling vehicles at supersonic speeds.

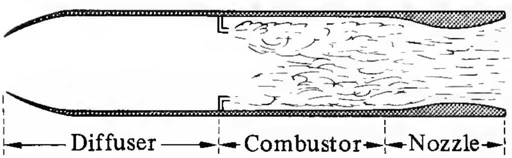
One other significant difference between rockets and ramjets is thrust at zero speed. Rockets can deliver thrust at any speed, even standing still, whereas a ramjet requires an auxiliary boost system to accelerate it to its supersonic operating regime so that its forward motion can compress the inlet air. To operate at practical efficiency a ramjet must be moving at about Mach 1.5 or greater so that the margin of thrust over drag will be satisfactory.

MACH NUMBER

The Mach number is the ratio of the speed of a body with respect to a surrounding fluid (such as air) to the speed of sound in the fluid. An aircraft travelling at Mach 2 is moving twice as fast as the local speed of sound. The Mach number may also be the ratio of the speed of the fluid to the speed of sound. A stream of air exiting from a ramjet diffuser may be moving at Mach 0.2 or about 150 miles per hour.

Ramjet Components

The basic ramjet engine consists of an air inlet or diffuser, a combustor, and an exhaust nozzle. The diffuser admits air to the engine, reduces the air velocity, and develops ram pressure. The combustor adds heat and mass to the compressed air by burning a fuel. The nozzle converts



Basic Components of Ramjet Engine

some of the thermal energy of the hot combustion products to kinetic energy to produce thrust.

Although the operating principle of a ramjet engine appears simple, both the equations that define ramjet parameters and the process by which a ramjet is designed are much more complex than those for a solid propellant rocket. Everything that happens inside a rocket is isolated from its external surroundings. Except for secondary effects of acceleration, flight maneuvers, or aerodynamic heating, internal processes of the rocket are independent of its environment. In fact, the only things affected by the atmosphere are vehicle drag and thrust level (which depends on the pressure at the nozzle exit plane). The thrust level can therefore be computed by equations that essentially depend only on the internal parameters of the rocket motor.

By comparison, in a ramjet engine the thrust level is subject to the dynamic interaction of several factors, including the pressure developed in the diffuser, angle of attack, vehicle velocity, and ambient pressure or altitude. This additional complication of operating parameters means that understanding how a ramjet works requires a modest exposure to certain principles of aerodynamics. Some of these principles will be touched on in the pages that follow.

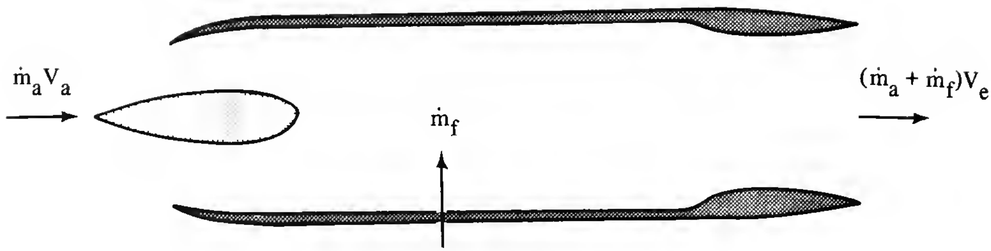
Operating Principle

A discussion of a ramjet engine can be simplified by assuming that the ramjet is stationary, and that air approaches the engine at a velocity equal to the vehicle speed. As air enters the inlet, adiabatic compression causes an increase in temperature and a decrease in velocity.

> **ADIABATIC COMPRESSION**
>
> The reduction of volume of a substance without heat flow, in or out.

The air is further heated by combustion of the fuel which also increases the mass flow, typically between 5 and 10%. The high-temperature compressed gases then are expanded in the nozzle and accelerated to high velocity. The thrust developed by the engine is the net rate of change of momentum of the gases passing through the engine and is equal to the mass flow rate of the air plus burned fuel times the jet velocity minus the flow rate of air times the air velocity. The effective net thrust on the vehicle will be somewhat less than the engine thrust because of skin friction drag on the air flowing around the ramjet vehicle.

The overall process can be more clearly understood by examining the thrust equation. Let $\dot{m}_a$ be the mass rate of flow of inlet air and V_a be its velocity. Then $\dot{m}_a V_a$ is the momentum rate of the inlet air stream. The exhaust gas is coming out of the nozzle at a velocity V_e, sometimes



$\dot{m}_a$ = mass rate of flow of inlet air

$\dot{m}_f$ = mass rate of flow of fuel

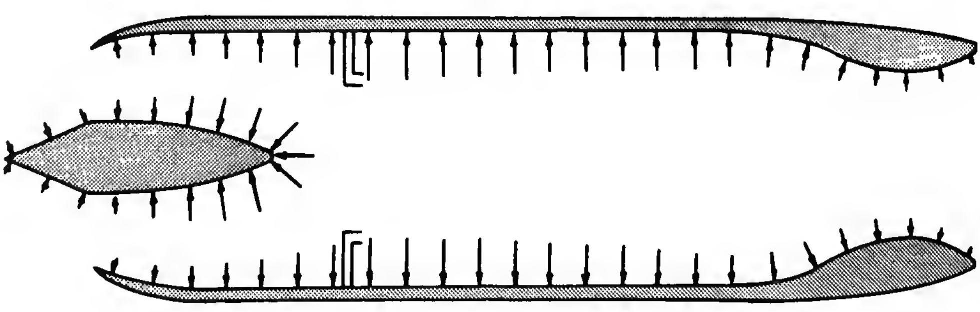
V_a = velocity of inlet air

V_e = velocity of exhaust stream (sometimes designated V_j or c)

referred to as the jet velocity, V_j. The momentum rate of the exhaust gas is $(\dot{m}_a + \dot{m}_f) \cdot V_e$ where $\dot{m}_f$ is the rate of mass addition in the engine due to burning the fuel. The thrust of the engine is, therefore, simply the net rate of change in momentum at a steady state condition and is given by:

$$F = (\dot{m}_a + \dot{m}_f)\, V_e - \dot{m}_a V_a$$

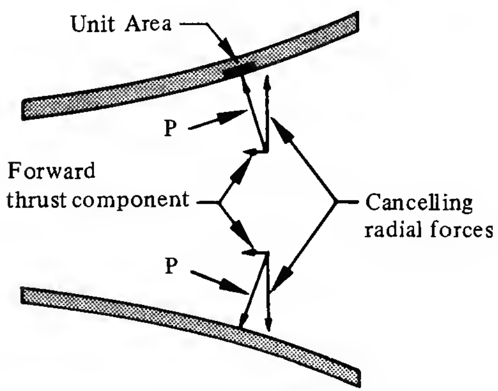
This equation for change of momentum in a ramjet bears further examination, since each term affects the complex interactions associated with ramjet operation. First, the exhaust velocity V_e is identical with the symbol c commonly used for exhaust velocity of a rocket engine. In both ramjets and rockets, $c = c^* C_F$, where c^* is the characteristic exhaust velocity and C_F is the nozzle thrust coefficient. The value of c^* obtained from theoretical calculations is a measure of the energy available from the propellant and depends on combustor pressure, mixing efficiency, and residence time. The value obtained under test conditions thus becomes a measure of combustion efficiency. C_F depends on pressure in the combustion chamber (hence on velocity, altitude, and inlet efficiency in ramjets) and on nozzle



Distribution of Internal Pressure in a Ramjet Engine

RESOLUTION OF FORCES IN A RAMJET

The force causing the increase in momentum of the inlet air acts in the same direction as the air stream and appears as a pressure drop in the ramjet. Now, the pressure at any point in the duct is perpendicular to the surface. Since the product of pressure and area is force, for each unit area of surface there is an applied pressure and a corresponding force. Each of these force vectors can be resolved into radial and longitudinal components. The radial components cancel, but the longitudinal components are algebraically additive. The resultant longitudinal force is directed forward and equals the thrust of the ramjet, which is numerically equal but opposite in direction to the force causing the change in momentum of the air stream.



Resolution of Forces for Pressure Applied to Unit Area of a Duct

configuration.

The term V_a is flight speed, sometimes expressed in terms of Mach number. Although the equation shows V_a causing a decrement in thrust, this negative term is offset by the term containing $\dot{m}_a$, $\dot{m}_f$, and V_e, all of which are direct functions of V_a. In fact, if V_a is zero, the thrust is zero. As V_a increases, the term $(\dot{m}_a + \dot{m}_f)V_e$ increases more rapidly than $\dot{m}_a V_a$ so thrust increases steadily and usually becomes maximum in the range of Mach 3 to Mach 5. Thereafter the negative term begins to dominate, so thrust falls off.

For these reasons, ramjet thrust calculations are considerably more complicated than those for rockets. In making such calculations it is convenient to convert the familiar conservation equations of mass, momentum, and energy to forms involving Mach number and to combine them into expressions

STREAM THRUST

A fluid flowing through a conduit is subject to three forces: the pressure acting over the bounding end surfaces and the force exerted by the inner surface of the conduit. The resultant of these forces is equal to the rate of change in momentum of the fluid. For calculations involving the thrust due to a moving fluid it is convenient to regard the sum of the pressure-area force and the rate of change of momentum as a single term, called the stream thrust. For example, at a point x the stream thrust may be defined as:

$$F_g = \mathcal{J}_x - \mathcal{J}_o - p_o (A_x - A_o)$$

F_g = gross thrust of the ramjet

$\mathcal{J}_x$ = stream thrust for the internal flow at station x

$\mathcal{J}_o$ = stream thrust for the internal flow at station 0

p_o = ambient pressure

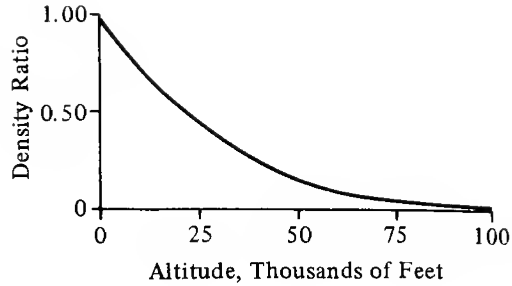
A_x = cross-sectional area at station x

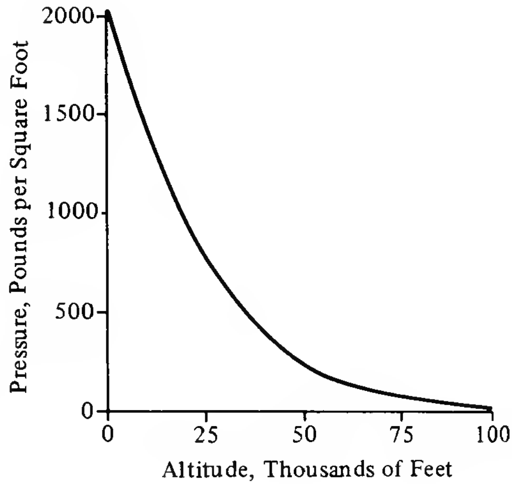
A_o = cross-sectional area at station 0

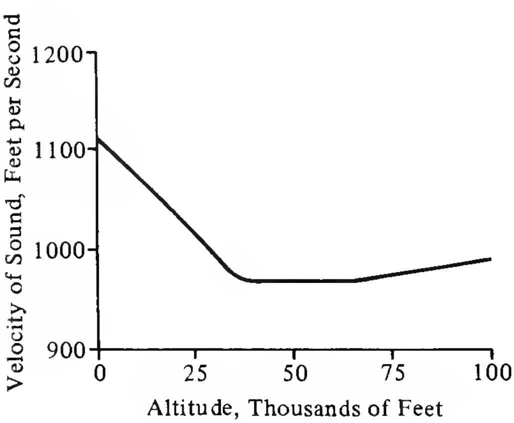
PROPERTIES OF THE ATMOSPHERE

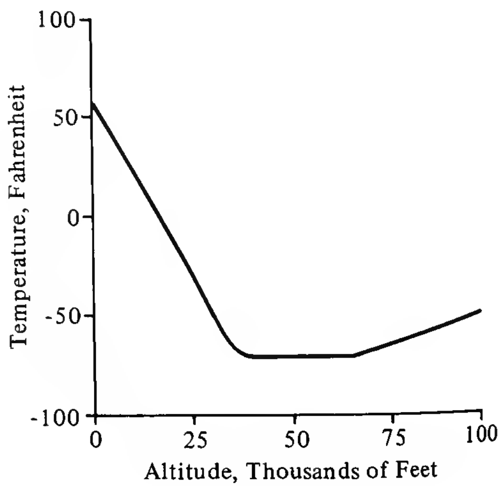
The atmosphere that a ramjet engine encounters over its range of operating altitudes is quite different from what we experience near sea level. Air density atop the tallest mountains (about 35,000 feet) is only 31 percent of the density at sea level. At 100,000 feet it is less than 2 percent. The pressure exerted by the atmosphere also decreases with altitude. From a value of over 2100 pounds per square foot (14.7 pounds per square inch) at sea level it is reduced to only 23 pounds per square foot at 100,000 feet.

The temperature of the atmosphere behaves quite strangely. Starting from a value of 58 F at sea level it decreases steadily till at an altitude of 36,000 feet it has fallen to -68 F. From 36,000 to 65,000 feet the temperature is constant. From 65,000 to 100,000 feet (which approaches the upper operating limit for ramjets) the temperature rises slightly. Above 100,000 feet it rises to 170 F at 180,000 feet, than falls to -28 F at 260,000 feet, and rises again to 188 F at 380,000 feet.









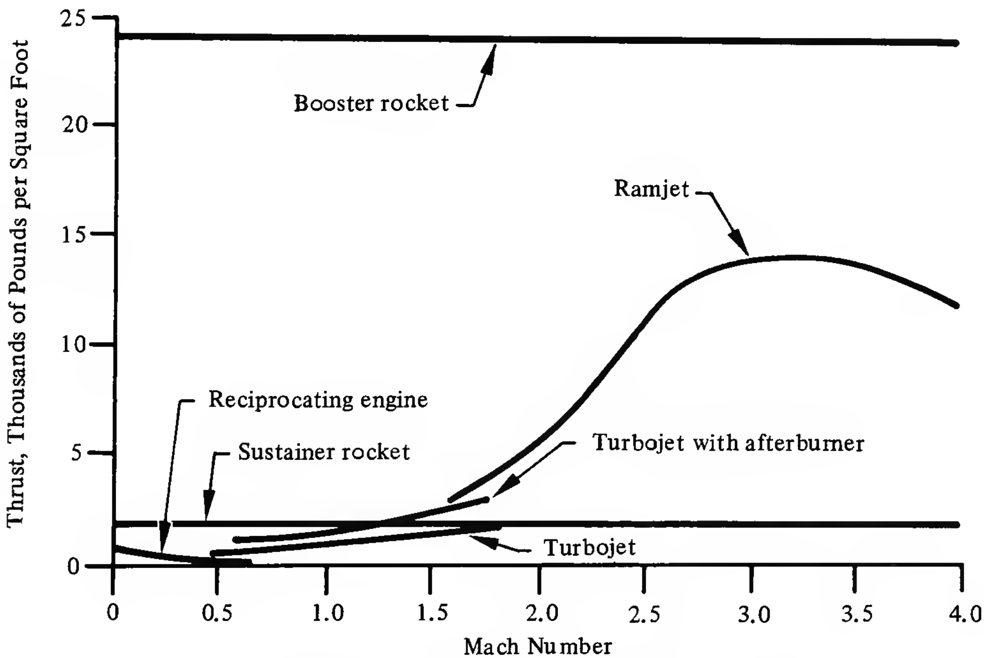
CHOKED FLOW

When flow in a duct or passage is such that the flow upstream of a certain critical section cannot be increased by a reduction of downstream pressure, the flow is said to be choked.

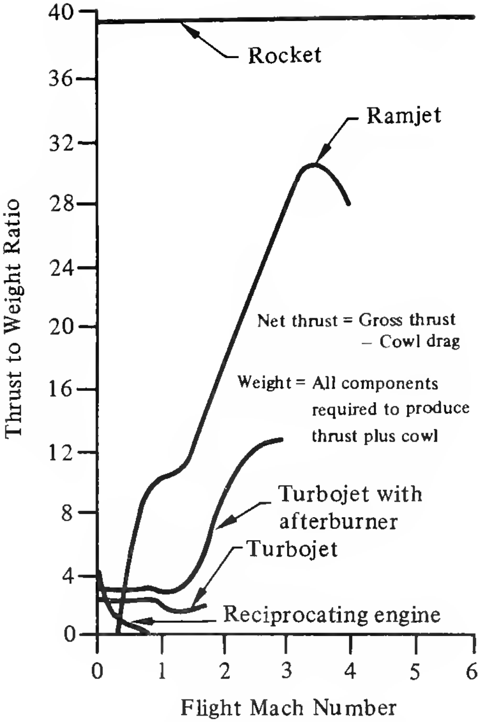
employing the stream thrust as a parameter. The stream thrust is a particularly useful quantity in ramjet calculations because the difference in stream thrust between two stations is equal to the thrust exerted in an axial direction on the duct walls between the two planes. Moreover, when the local Mach number is unity, as at a throat or choking section of the duct, the stream thrust becomes a direct measure of the exit stream thrust of a ramjet equipped with a non-expanding exit nozzle. Thus, stream thrust for unit mass flow and nozzle area depends only on thermodynamic characteristics of the exhaust gas. It is therefore a useful measure of the combustor performance (analogous to the characteristic velocity, c*, employed for rocket engines).

Operational Characteristics of Propulsion Systems

Selecting a vehicle propulsion system involves consideration of many aspects of its performance and use. The performance characteristics of primary importance are (1) thrust per unit frontal area, (2) thrust per pound of engine



Thrust per Unit Frontal Area for Propulsion Systems



Thrust to Weight Ratio
for Propulsion Systems

weight, (3) fuel consumption rate per pound of thrust, and (4) speed and altitude boundaries for efficient operation. To these performance characteristics must be added such considerations as cost, flexibility in installation, and reliability.

Since the lift-to-drag ratio of supersonic vehicles is one quarter or less that achievable in subsonic types, the thrust required for a high speed vehicle to carry a given payload becomes relatively large. Engine drag thus becomes a significant part of the overall drag, so thrust per unit frontal area is a characteristic of primary importance in engine selection. Above Mach 2, ramjets are superior to turbojets or sustainer rockets, which generally have relatively low thrust-to-weight ratios, in terms of this parameter.

The same reasons that make thrust per unit area important for supersonic propulsion apply to the thrust delivered per pound of engine weight. In this respect ramjets are markedly superior to turbojets.

Fuel specific impulse determines the range of the vehicle and is accordingly the principal discriminator for long range missions. For short range applications it may be of little significance since other factors, such as available volume of the vehicle, may be dominant. The fuel specific impulse of ramjets is relatively poor compared to other airbreathers until speeds above Mach 1.5 are reached, but above this point it is superior to that

SPECIFIC IMPULSE

The specific impulse is the number of pounds of thrust delivered by one pound of propellant burning in one second. Specific impulse is given in seconds. In ramjets, the propellant is simply the fuel.

$I_a = F_g / \dot{W}_a$

$I_f = F_g / \dot{W}_f = I_a / f$

I_a = air specific impulse

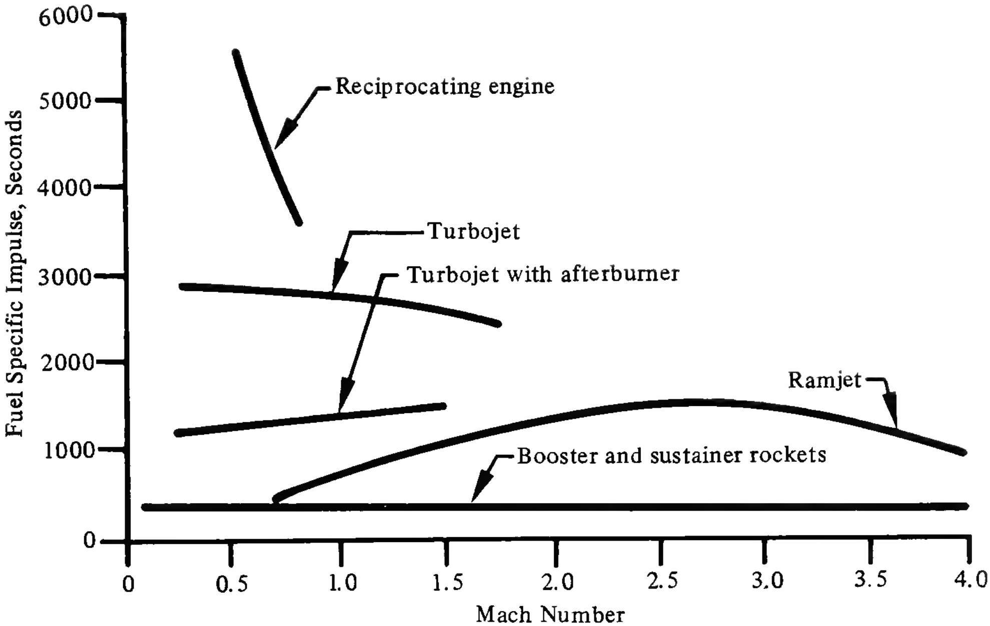
I_f = fuel specific impulse

F_g = gross thrust (due to the internal flow)

$\dot{W}_a$ = weight rate of flow of air

$\dot{W}_f$ = weight rate of flow of fuel

$f = \dot{W}_f / \dot{W}_a$ = fuel-air ratio



Fuel Specific Impulse for Propulsion Systems

of all other chemical propulsion systems.

By comparison, the specific impulse of rocket propellants at sea level is about 250 seconds. These propellants contain more oxidizer by far than fuel (typically 70 to 80% of total propellant weight). It would therefore be expected that the specific impulse of a ramjet would be several times as great because no oxidizer has to be carried on board. In fact, the specific impulse of common fuels in ramjets is from 1000 to 1500 seconds over the normal range of flight Mach numbers.

As the speed of ramjets is increased over about Mach 4, the rapid increase in air stagnation temperature causes design difficulties due to structural heating.

STAGNATION TEMPERATURE AND PRESSURE

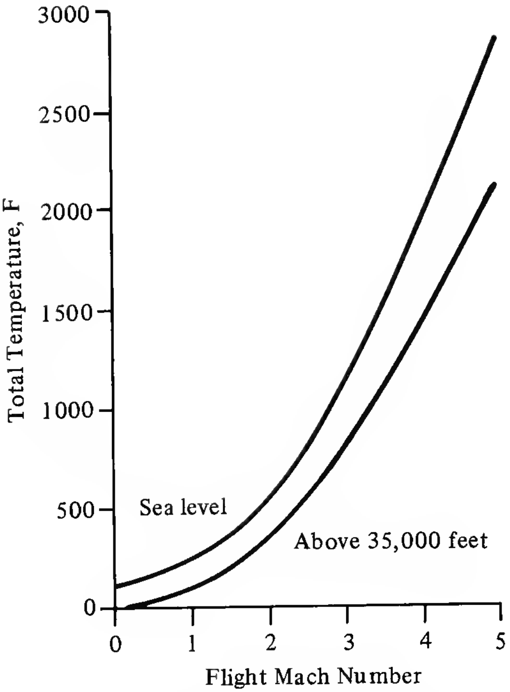
When a gas is decelerated so that its final speed is zero, its kinetic energy of motion is converted partially to an increase in static pressure and partially to heat. Its temperature rises to a final value termed the stagnation temperature, which is related to the Mach number of the gas before deceleration. The stagnation pressure is the static pressure achieved under these conditions.

$T = t_o (1 + 0.2M^2)$

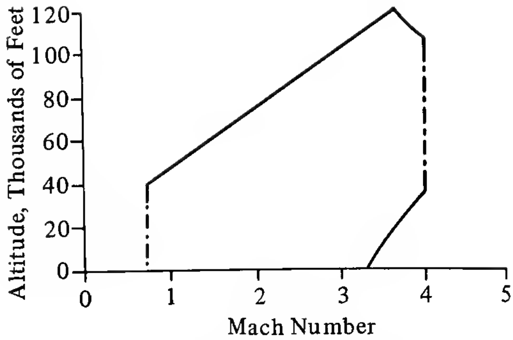
T = stagnation temperature in degrees Rankine (Fahrenheit plus 460)

t_o = local air temperature in degrees Rankine

M = flight Mach number



Stagnation Temperature as a Function of Flight Mach Number



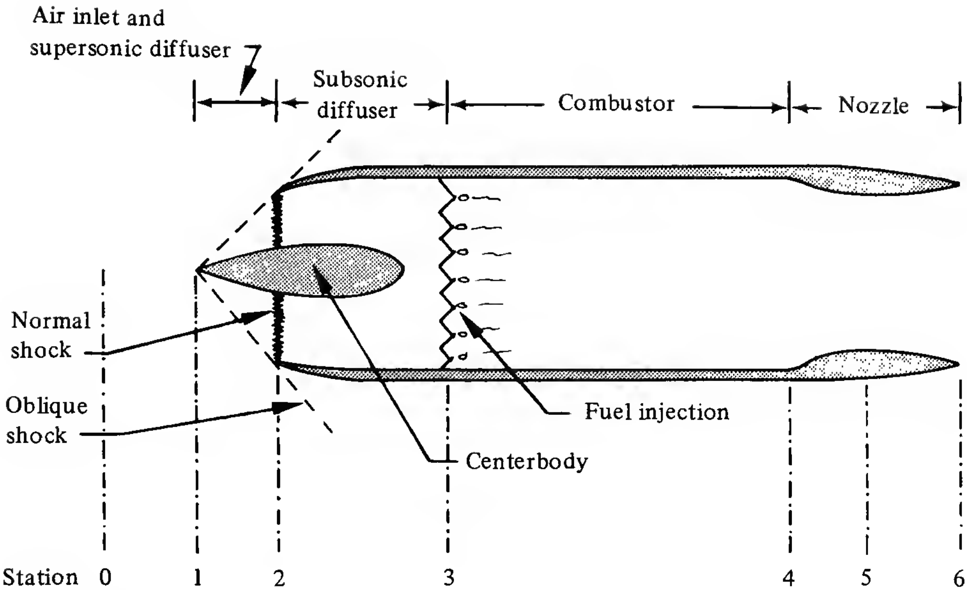
Ramjet Operating Limits*

*Assumptions
Conventional (hydrocarbon) fuel
Uncontrolled aerodynamic heating
Subsonic combustion

Higher heat transfer rates in denser air cause the temperature limit to be reached at a somewhat lower speed at sea level. At the "thermal boundary," about Mach 4, materials problems for both airframe and engine become severe. Unless active cooling were provided, the vehicle would have to operate at a red heat and would have to be made from expensive high-temperature metal alloys. Furthermore, there is a loss of fuel effectiveness in heating air that is already very hot. Thermal efficiency of the engine decreases because of dissociation of the products of combustion into molecular fragments. This process absorbs energy and therefore limits the temperature rise that can be attained in the engine.

The altitude ceiling is reached when pressure in the combustion chamber falls too low for efficient combustion. Moreover, in most vehicle designs a somewhat lower ceiling would be imposed by the need for air pressure to provide lift and maneuverability for the vehicle. The most serious drawback of the pure ramjet is its inability to produce thrust at zero speed and the accompanying strong dependence of thrust on flight velocity. Evaluation of ramjet applications must, therefore, always consider the combination of ramjet and boost power plant and judge the combination in terms of fuel economy and engine weight.

Although subsonic ramjets are feasible, their performance is low, so it is in the supersonic flight regime that ramjets display advantages over other propulsion systems. Most of the discussion in the following pages will therefore be based on supersonic ramjets.



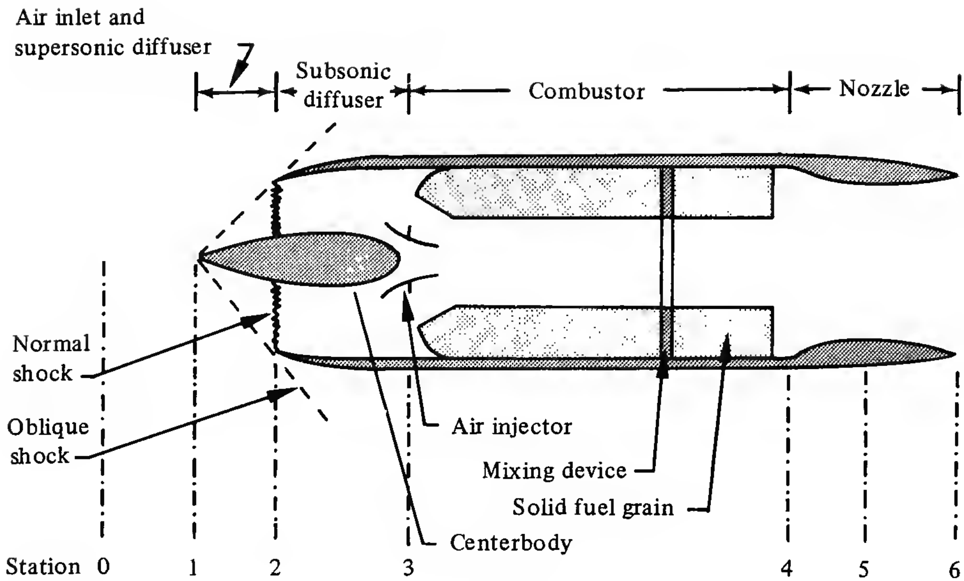
Station Number	Location
0	Vehicle flow field immediately upstream of the air induction system
1	Capture station - beginning of internal flow system
2	Cowl lip
3	Diffuser exit - combustor entrance
4	Combustor exit
5	Nozzle throat
6	Nozzle exit

Liquid-fueled Ramjet Nomenclature

Production costs of ramjet engines tend to be low in comparison with turbojet or piston engines because of the lack of rotating machinery. In addition, the large advantage of ramjet engines in thrust per pound of engine weight leads to significant cost savings for systems with the same thrust level.

Efficient design of supersonic vehicles requires close coordination of the interface between power plant and airframe. Designing airframe and power plant as a unit accordingly places a premium on engine flexibility in redesign to accommodate desired changes in dimensions or performance. Because of the simplicity of the ramjet, small changes in scale or performance may usually be accepted without extensive redesign, retooling, or test programs.

No power plant, however attractive from the standpoint of performance or operating characteristics, can succeed in commercial or military applications unless it is reliable. The need for reliability in complex power plants or



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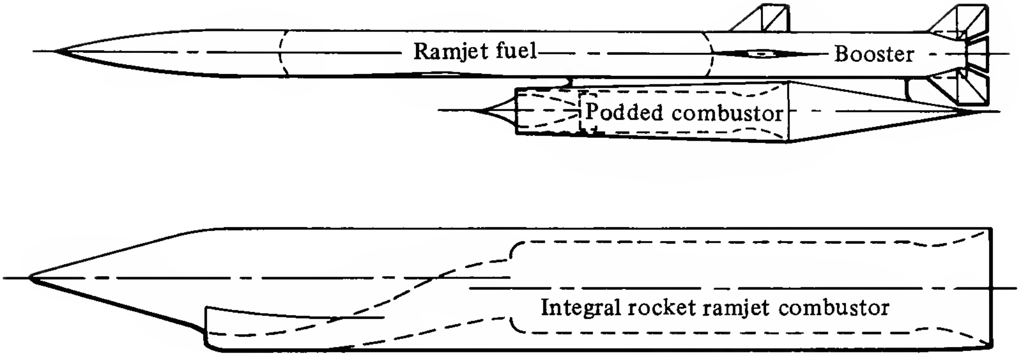
Solid-fueled Ramjet Nomenclature

those requiring close tolerances tends to result in extensive quality control, hence greater cost and decreased production rates. The simplicity of the ramjet engine, with its complete absence of moving parts exposed to hot gases, makes it extremely attractive in this regard.

Liquid-fueled Ramjets

The characteristics that distinguish the liquid-fueled ramjet (LFRJ) are the fuel delivery system, with which fuel is introduced, and the combustor, which includes a flameholder, the combustion zone where heat is released, and a nozzle through which the burned gases are ejected rearward at high velocity. The LFRJ requires a separate fuel storage system that can supply fuel to the delivery system. There must also be a fuel control system to adjust fuel rate to air rate (which varies with vehicle altitude and flight speed) and control flight speed of the vehicle as desired. Some form of auxiliary power supply must be provided



Typical Engine Configurations

to furnish power to drive the control system.

Solid-fueled Ramjets

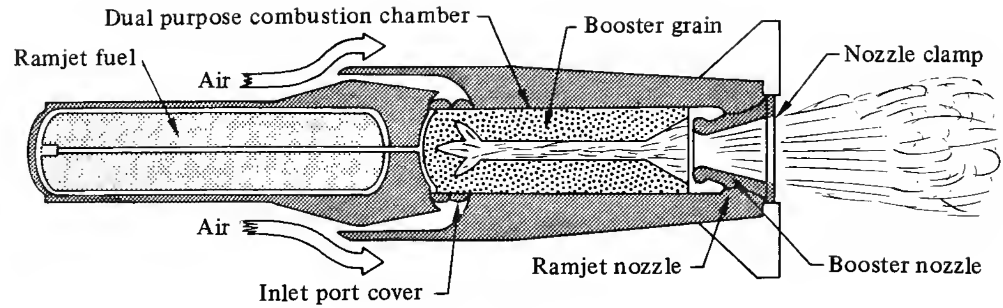
Solid-fueled and liquid-fueled ramjets are related in the same way as solid-propellant and liquid-propellant rockets. The main characteristic that distinguishes the solid-fueled ramjet (SFRJ) is the absence of fuel tankage, delivery, and control systems, since the fuel is entirely contained in the combustor at the beginning of the duty cycle. In addition, the combustor is usually simpler because there is no liquid phase fuel to be atomized and mixed with air in the combustor. Instead, there is an air injector to increase the turbulence of the air as it enters the combustor so as to improve flameholding. There may be a mixer to ensure that fuel-rich and air-rich gases are thoroughly mixed to improve combustion efficiency, which is always a key consideration in any combustion process involving a gas and a solid.

Integral Rocket Ramjets

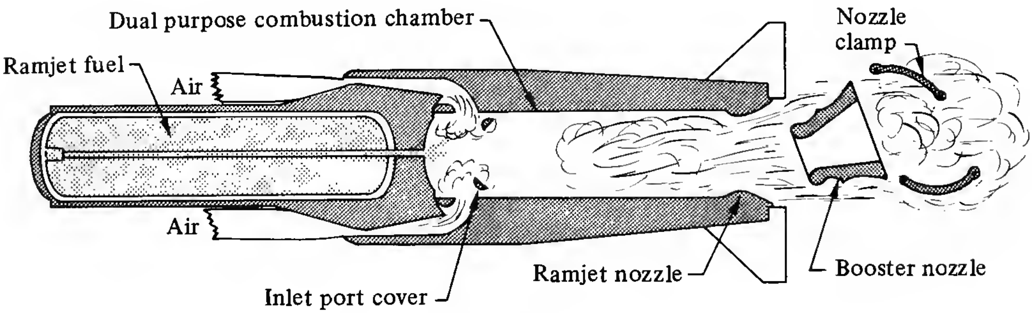
Early ramjet systems employed a separate detachable booster to achieve ramjet takeover speed. However, this scheme was not always well suited to launcher installations or to other operational requirements. For example, it meant dropping a fairly heavy piece of hardware earthward, so launches were limited to uninhabited areas.

Dependence on a tandem booster ceased with the conception of the integral rocket ramjet (IRR), successfully reduced to practice by CSD, which employs a dual-purpose combustor that first serves as a rocket combustion chamber for booster propellant cast into it. The propellant burns and accelerates the vehicle to a high speed. Then inlet air is allowed to enter the combustor where it encounters either a liquid or a solid fuel. The fuel then burns in the combustor in the normal manner of a ramjet.

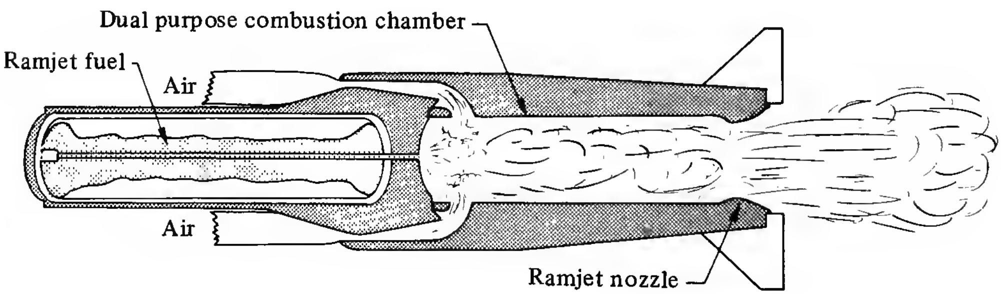
Because the boost rocket operates at 1000 to 2000 pounds per square inch and



Booster Operation



Transition



Ramjet Operation

Operating Sequence of Integral Rocket Ramjet the sustain ramjet operates generally at less than 100 pounds per square inch, two nozzles are normally required. Moreover, since the boost nozzle has a smaller throat diameter than the ramjet, the boost nozzle must be expelled before ramjet operation begins. This scheme of operation is quite workable; however, some other techniques that achieve the same overall effect of boost-sustain operation are available (and will be described later).

The simplicity of the IRR makes it aerodynamically "cleaner," more reliable, and lighter than a ramjet with a separate booster. In some form the IRR will doubtless be one of the leading propulsion systems of the 1980s.

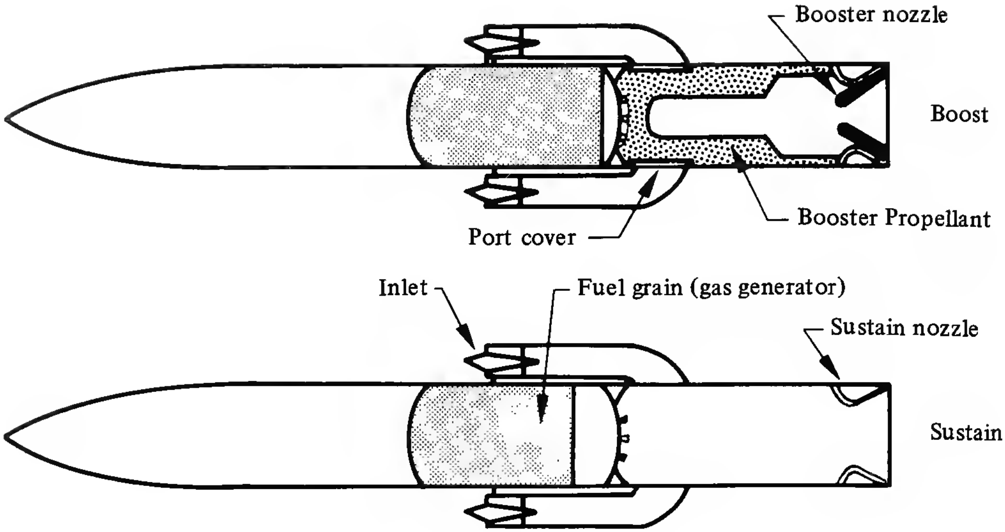
Ducted Rocket

Strictly speaking, the ducted rocket is not a ramjet. However, it is an airbreathing close cousin and its operational characteristics are so similar to a ramjet that the two systems can be considered together for all practical purposes. The configuration of the ducted rocket can be considered similar to an LFRJ whose fuel tank is replaced by a fuel-rich solid propellant grain. The amount of oxidizer in the grain is just sufficient to sustain combustion in the absence of air. The fuel-rich gas generated by the grain mixes with inlet air in the combustor, or aft mixer, and is exhausted through the nozzle. The major problem is to mix air and exhaust gas streams thoroughly so as to obtain high combustion efficiency. The advantage is that the ducted rocket can attain higher thrust margins at low supersonic speeds than the integral rocket ramjet. The ducted rocket's performance depends greatly on air inlet angle and velocity, Mach number of the gas from the solid fuel gas generator, impingement angle, and air/propellant ratio. The significant difference between fuel grains for the SFRJ and the ducted rocket is that the ramjet grain does not sustain combustion without air, since it normally contains little or no oxidizer. The ducted rocket grain supports combustion (because of a higher oxidizer content), so many of the ramjet-oriented problems relating to flameholding and recirculation are not as important.

THRUST MARGIN

The thrust margin is the ratio of the difference between thrust and vehicle drag to the vehicle drag. The term therefore indicates the fraction of thrust (as a function of drag) available to accelerate the vehicle in level flight. If climb is involved, the thrust margin must also include a term for weight.

In principle, because the ducted rocket contains part of its oxidizer, it does not have a performance potential as high as a pure ramjet. This disadvantage is offset by increased operational flexibility. The ducted rocket therefore represents one of the simplest forms of ramjet-type engines in that there is a reduced dependence on flight parameters. In most applications the ducted rocket is used with an integral rocket booster, so the combustor functions initially as a chamber for a solid propellant rocket motor. It is advantageous if the ducted rocket



Ducted Rocket Configuration

combustor can be made to operate efficiently without mixing aids or flameholding devices, thus eliminating the problems of trying to fit a solid booster grain in and around the various aids and devices. Moreover, the axial momentum of the effluent from the fuel generator can be preserved and combustor pressure losses can be minimized while achieving complete combustion and mixing and therefore high combustion efficiency.

3 Air Induction Systems

The diffuser transforms the kinetic energy of the air entering the engine into a pressure rise, called the ram pressure. The magnitude of the ram pressure is a function of flight speed and the design characteristics of the supersonic and subsonic sections of the diffuser.

When the ramjet is operating, air from the atmosphere enters the engine. After the velocity of the air has been reduced and its static pressure increased by the supersonic diffuser, the air enters the subsonic diffuser and is compressed still further. It then flows into the combustor where it is heated to 3000 to 4000 F by continuous combustion of fuel. The hot gaseous products of combustion are then expanded in the exhaust nozzle section and are ejected from the engine with a velocity exceeding that of the entering air.

In the usual ramjet, the air approaching the engine at supersonic speed must be slowed to a subsonic value low enough that it will not blow out the flame in the combustor. A linear supersonic flow can be reduced to a subsonic flow only if it passes through a normal shock wave. It is characteristic of a shock wave that the subsonic flow leaving the shock is at a higher static pressure than the supersonic flow entering. In all cases, shock waves are accompanied by a decrease in available energy: the stronger the shock, the greater the decrease. However, the flow at supersonic velocity can be reduced to subsonic velocity by causing the supersonic flow to pass first through one or more oblique shocks and finally through a weak normal shock. Under these conditions the loss in available energy is smaller, and the flow leaves the weak normal shock at a velocity slightly less than Mach 1.

The subsonic diffuser (through which the stream must pass next on its way to the combustor) further reduces the Mach number of the flow to about 0.2 to 0.4 at the entrance to the combustor. Because of this deceleration there is an additional rise in the static pressure above the rise resulting from the shock waves.

Ideally, a diffuser configuration should be chosen that will compress the supersonic approach stream with continuous reduction of the air speed to a final value appropriate to the through duct. The diffuser should do this by converting the kinetic energy of the stream to pressure energy with no energy

PRESSURE DISTURBANCES — SHOCK WAVES

A disturbance originating from a source is propagated in all directions at the speed of sound through the fluid surrounding the source. If the source is moving at subsonic speed, it is in effect trying to catch up with the sound waves (disturbances) that its motion produces. At subsonic speed, however, the acoustic speed is always larger than the speed of the moving body or source. The body therefore always moves into a fluid that has already undergone changes because of the motion of the body. That is, the fluid ahead of the body may be said to become aware of the presence of the body because the latter propagates disturbance signals ahead of itself. Thus, when a body moves at subsonic speeds, the disturbances it creates are said to clear away from it.

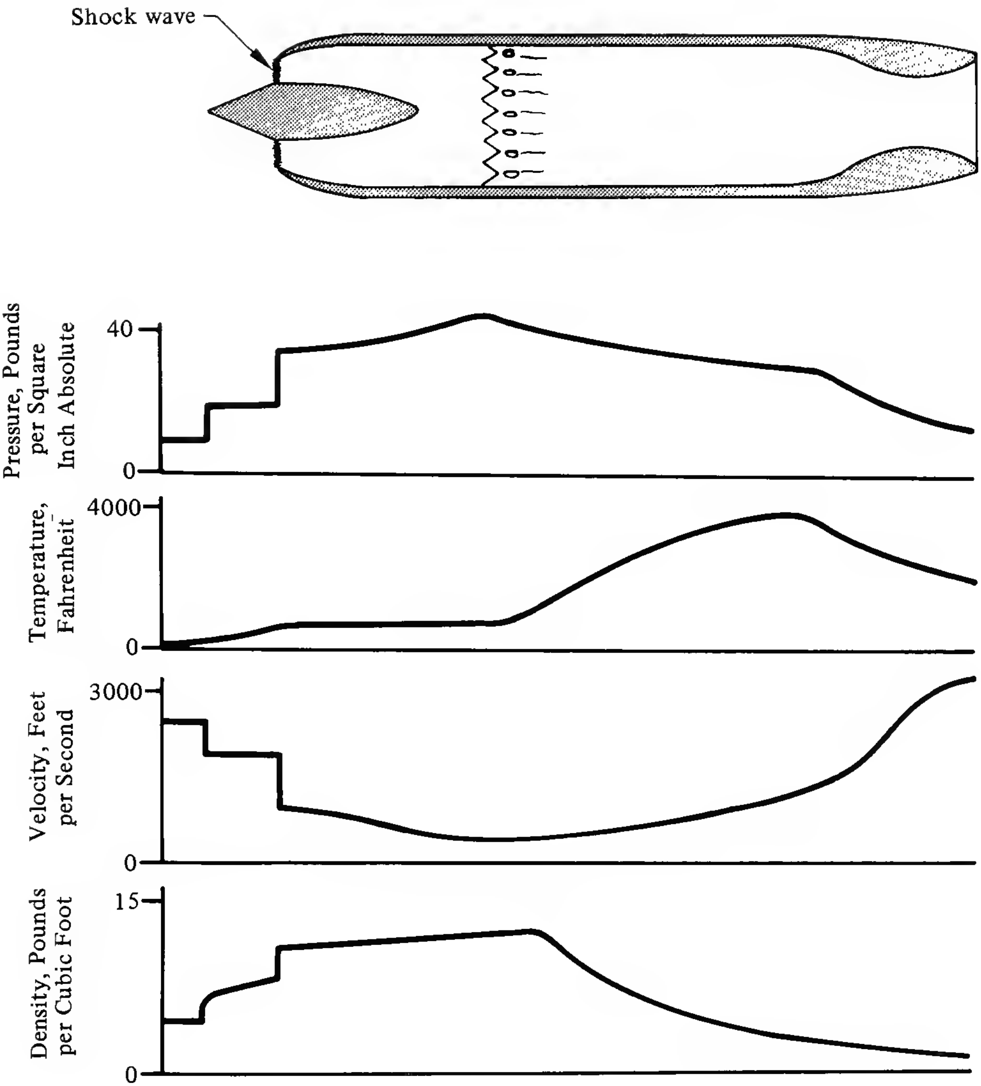
The situation is quite different when the body moves at supersonic speed. The wave front of the disturbance created by the body lags behind the point on the body that created the disturbance, so the disturbance wave front cannot overtake the moving body. Consequently the moving body is always outside and ahead of the disturbance wave front it produced. The different disturbance wave fronts are enveloped by a conical surface, called a Mach cone, the shape of which is related to the speed of the body. When a body moves with supersonic speed, all of the disturbances in the flow are confined to the Mach cone. In the regions outside the cone, the fluid medium is unaffected by the moving body. The conical separating surface therefore forms a wave front called a Mach wave, which is a weak compression shock.

In the wave system formed at the nose of a vehicle moving at supersonic speed the wave front is very steep. In traversing the wave there is a large pressure rise, called a shock wave. The shock phenomenon is a more or less instant compression of the gas, so it is not a reversible process. Energy for compressing the gas flowing through the shock wave is derived from the kinetic energy that the gas possessed before the shock. Because the process is irreversible, the kinetic energy of the gas leaving the shock is less than that corresponding to reversible compression between the same pressure limits. The reduction in kinetic energy appears in heating the gas to a temperature above that for the reversible compression process. Accordingly, there is a decrease in the available energy of the gas.

There are several different kinds of shock waves, each with particular characteristics. In some cases the shock wave is stationary with respect to the body upon which it is formed. This shows that the speed of propagation of the shock wave is equal to the speed of the body, otherwise the stationary relationship could not be maintained. When the shock wave is formed so that it is perpendicular to the direction of the flow, it is termed a normal shock (here "normal" is used to mean "perpendicular" rather than "usual").

In many situations involving shocks, the direction of a supersonic flow is changed sufficiently that the gas is compressed in such a way that a shock front is formed that is inclined with respect to the initial flow direction. Such shocks are termed oblique or angle shocks. Where an oblique shock is formed, the fluid stream is deflected toward the shock.

losses. There are several types of diffusers that can fulfill this function satisfactorily. The particular type that is "best" depends on Mach number (that is, air speed of the ramjet). Some diffusers with favorable internal flow may cause unacceptably high external drag. The optimum performance of many diffusers is shown only at or near a single design point and worsens rapidly with changes in angle of attack or Mach number. Practically, the diffuser must usually be selected to



Gas Properties in a Ramjet Engine

perform well over a range of Mach numbers and angles of attack.

Since the steady state performance of supersonic diffusers is well understood, they may be designed for accurately predictable air flow reception and pressure recovery under steady-state conditions. Time-dependent phenomena are less well understood. For example, spike diffusers operating at an off-design condition sometimes display an oscillatory phenomenon in which part of

ANGLE OF ATTACK

The angle of attack is the angle between a reference line fixed with respect to an airframe (usually the longitudinal axis) and the direction of movement of the body. The angle of attack affects ramjet performance because the incident air stream is no longer parallel to the diffuser centerline, so the inlet shock train is shifted. This shift must be taken into account by the inlet design.

the air compressed supersonically spills outside the inlet. This phenomenon, called "buzz," involves rapid forward and backward movement of the shock pattern at the diffuser inlet. This movement is accompanied at high Mach numbers by pressure oscillations that may be of destructive intensity.

Problems also exist in designing and testing unsymmetrical configurations such as scoops or off-axis inlets. Moreover, when the diffuser is sufficiently close to the combustor, asymmetries in the subsonic flow of the inlet can affect combustor operation.

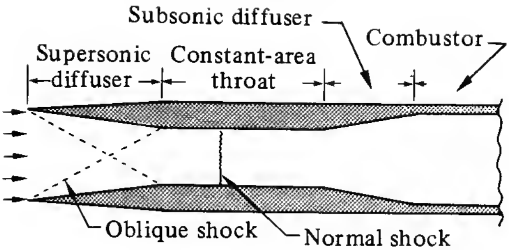
Inlet Designs

One of the most difficult problems in designing ramjets is in connection with air inlet systems, especially for flight at very high speeds. With any type of system there is a problem of regulating the inlet flow of air as flight speed is varied. One solution is to vary exhaust nozzle area and also inlet area by mechanical means. However, the more usual scheme is to design the air intake so that the shock can travel back and forth to accommodate changes in air flow.

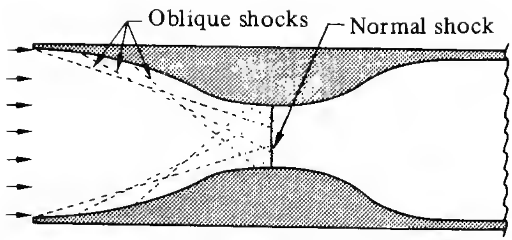
The design of air induction systems for supersonic airbreathing missiles is influenced by both external and internal factors. External factors include compatibility with the launcher, maximum allowable missile length and weight, restrictions on ground clearance of the aircraft, and placement of aircraft structures such as aerodynamic surfaces and landing gear. Internal factors to be considered include packaging of the missile guidance and control system, warhead, and propulsion system components. Even with all of these constraints the inlet must deliver an adequate supply of air to the engine over a wide range of flight operating conditions, and must do so with a compact, well-integrated design that offers both low cost and low drag.

To strike a reasonable balance among all of these conflicting requirements usually means designing an inlet for each new application. As a result, several types of inlets have been developed to meet various combinations of requirements.

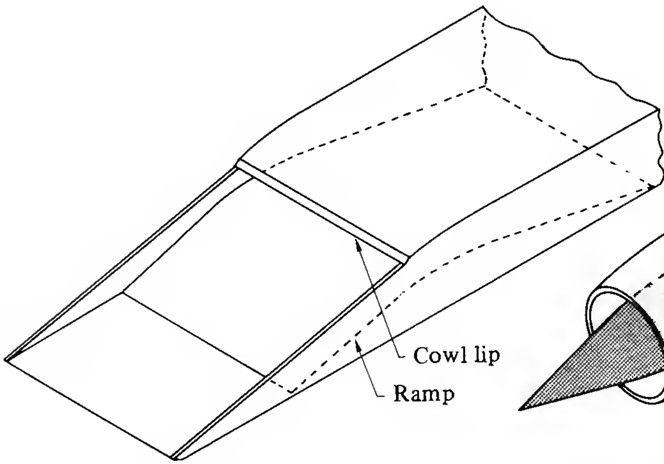
There are four basic types of inlets: normal shock, internal contraction, two-dimensional, and three-dimensional. A normal shock inlet is essentially a circular duct, slightly smaller in diameter at the leading edge. Since there is no supersonic diffuser, the transition of the inlet air from supersonic to subsonic flow occurs across the normal shock which resides at the inlet plane. The performance of this type of inlet is rather poor compared to inlets where external compression serves to weaken the normal shock at or near the cowl lip.



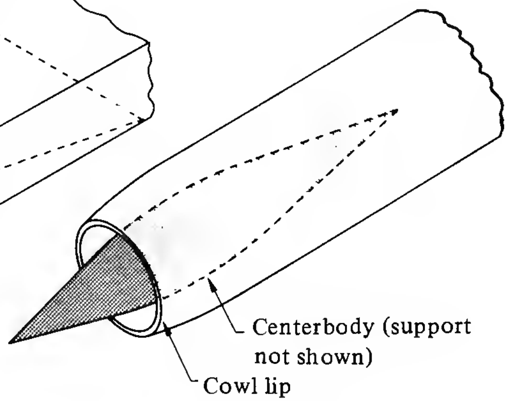
Internal Contraction Inlet
with Constant-area Throat



Internal Contraction Inlet
with Bell-shaped Entrance



Two-dimensional Inlet

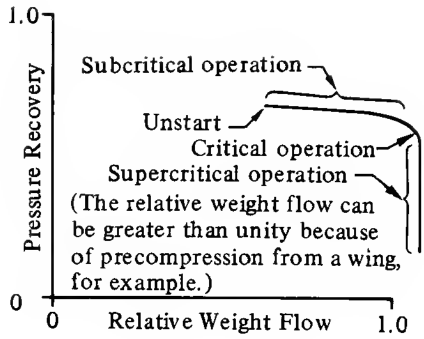


Axisymmetric Inlet

An internal contraction inlet is essentially an inverted rocket nozzle. A rocket nozzle accelerates subsonic exhaust gas to supersonic speed. The original high pressure of the gas is simultaneously reduced to atmospheric pressure, and the initial high temperature is reduced by about half. An internal contraction inlet decelerates supersonic inlet air to subsonic speed. Simultaneously it raises the temperature of the gas and compresses it from its original atmospheric pressure to some higher value.

For this type of inlet to perform efficiently, the strong normal shock in the throat should be weakened by oblique shocks upstream. This inlet theoretically gives the highest performance of any design at some single set of operating conditions. However, the normal shock tends to move in or out of the throat when the engine is operated off the design point. Accordingly, the throat is purposely elongated to help stabilize the normal shock. This inlet therefore does not operate as easily over a wide range of conditions as the types more generally employed. Despite its lack of flexibility, the internal contraction inlet is particularly good for such applications as artillery-type ordnance where constant velocity is maintained over a rather flat trajectory. The reason for its attractiveness for such applications is not only its high performance but also its low cost.

A two-dimensional inlet has a more or less rectangular cross section. The wedge-shaped supersonic diffuser consists of one or more ramps which turn



CRITICAL, SUPERCRITICAL, AND SUBCRITICAL OPERATION

There are three distinct conditions under which a ramjet engine diffuser can operate, depending on the heat released in the combustor. When the heat released is just enough that the back pressure at the exit section of the subsonic diffuser causes the normal shock to be positioned at the inlet thoats, the operation is said to be critical; this is the design condition.

Supercritical operation occurs when the heat released in the combustor is below the design condition. The back pressure at the outlet section of the diffusion system becomes too small to maintain the normal shock at the inlet. The excess pressure (or energy) associated with the internal flow must therefore be dissipated inside the diffusion system by a strong shock wave forming in the diverging portion of the diffuser. In other words the normal shock moves into the inlet.

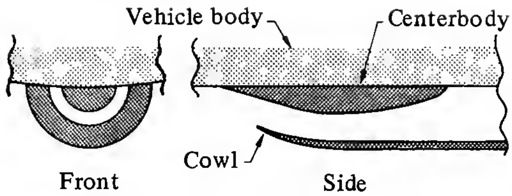
The opposite condition occurs in subcritical operation. If the heat release in the combustor is increased, the static pressure at the exit of the subsonic diffuser is greater than can be achieved under the design condition. The normal shock wave moves upstream, is expelled from the diffuser, and continues to move toward the vertex of the supersonic diffuser. Behind the normal shock wave the flow is subsonic. Since the shock wave is detached from the inlet the incoming air spills over the cowl of the diffuser, increasing vehicle drag and possibly leading to instability (buzz).

These three operating conditions can be related conveniently by means of a plot of pressure recovery versus relative weight flow of air. Pressure recovery is an efficiency factor, the ratio of the actual pressure immediately downstream of the diffuser to the theoretical stagnation pressure. Relative weight flow is the ratio of actual to theoretical weight flow. When one of these parameters is plotted against the other for actual ramjet operating conditions, a curve of characteristic shape is produced. Above the critical point (that is, in supercritical operation) the diffuser operates with poorer efficiency because the normal shock has moved into the inlet. However, ramjet operation is stable.

This range of stable operation is called the supercritical margin. As the relative weight flow decreases below that corresponding to critical operation (for example, because of an increase in drag that reduces Mach number), the normal shock moves out of the inlet and the inlet begins to operate subcritically. If the relative weight flow drops low enough, the engine will unstart. At the end of the transition from booster operation and the beginning of ramjet operation, the inlet must be operating within the supercritical margin for ramjet takeover to occur and stabilize.

the air flow, introducing oblique shocks which decelerate the flow until at or near the cowl lip (depending on the balance between design and operating conditions) a normal shock is finally formed.

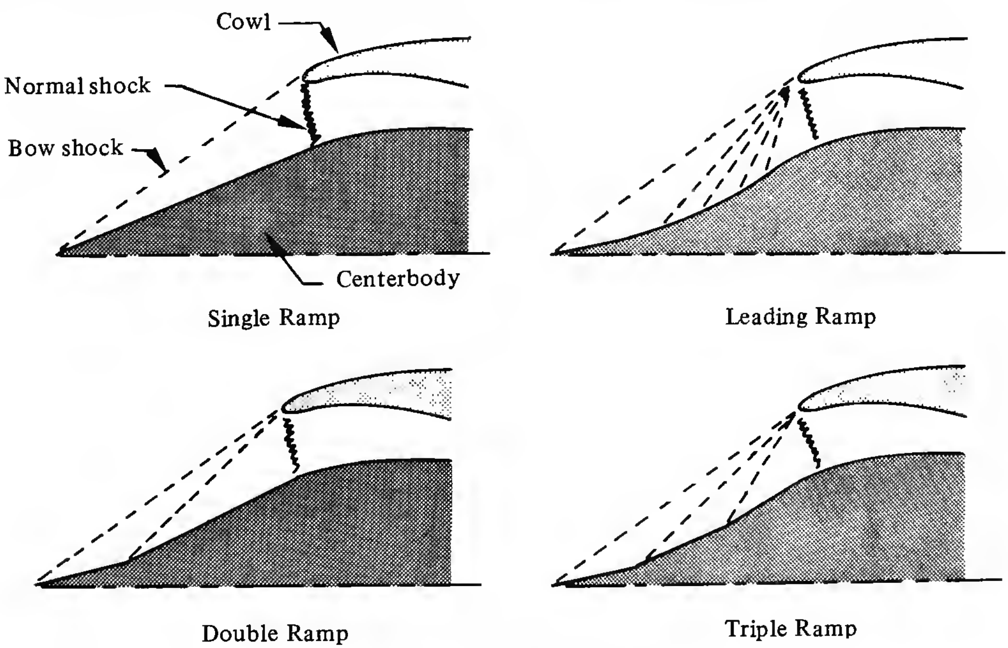
A three-dimensional inlet is either circular or elliptical in cross section. If it is circular, it is called axisymmetric and its diffusers have circular cross sections at any point along their length. The supersonic diffuser is essentially conical. A variation of the three-dimensional inlet is a half-axisymmetric inlet in which the diffusers are rounded rather than wedge-shaped.



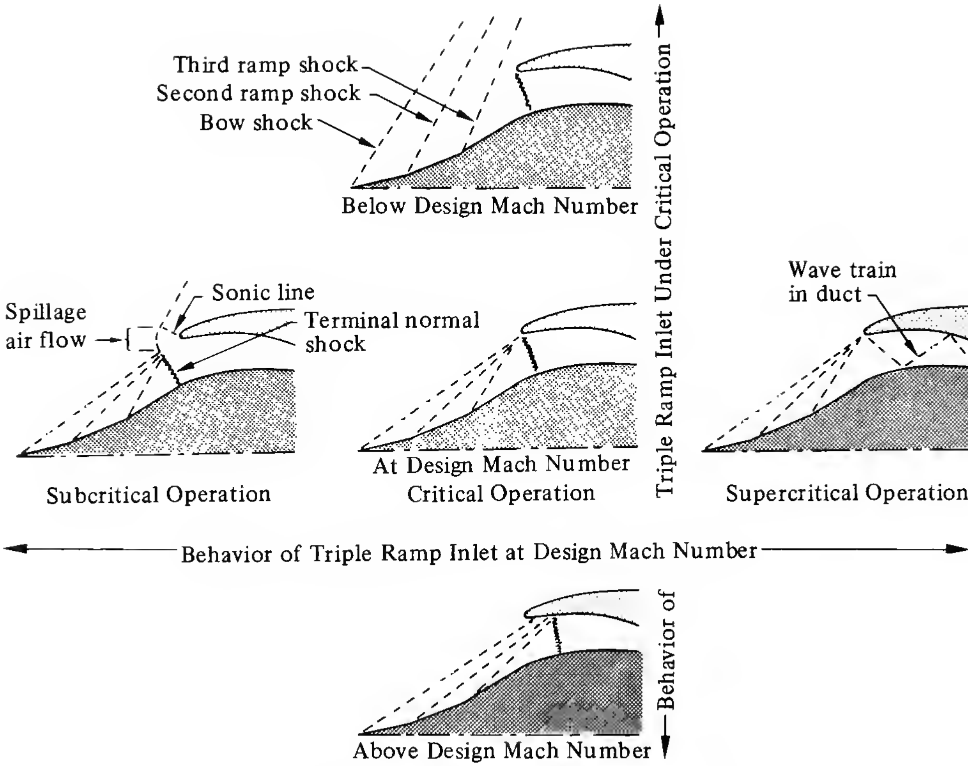
Half-axisymmetric Inlet

Behavior of Inlet Shock Train

The shock train in the inlet adjusts itself according to flight speed (inlet Mach number) and pressure requirements of the engine. If the pressure supplied by the diffuser for a particular operating condition equals the design pressure, the inlet is said to be in critical operation. If the pressure supplied is greater than the required pressure, the shock train moves into the inlet and the operation is termed supercritical. If the pressure supplied is less than the required pressure (subcritical operation), the shock train



Inlet Behavior at Design Mach Number



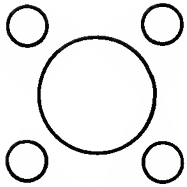
moves out of the inlet and causes the airflow to spill over, sometimes leading to instability ("buzz").

In some inlets employing internal compression a very troublesome phenomenon can occur. Under certain flight conditions when combustor pressure is raised too high, the normal shock can move so far upstream that supersonic flow inside the inlet is lost. When this happens the inlet loses its ability to compress the incoming air efficiently, causing a rapid loss of ramjet thrust and flight speed. This phenomenon is called an inlet unstart.

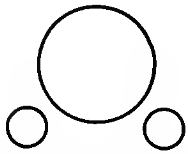
Sometimes it is possible to install the inlet under a wing or in the nose cone in the body flow field. The wing can then serve as a precompression device, making a rather efficient arrangement for the inlet. With precompression, both the relative flow rate and the pressure recovery can be greater than 100% of the performance of the isolated inlet.

Inlet Location

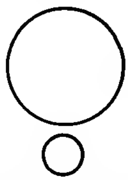
Inlets are usually located to give peak performance at the high angles of attack (5° to 10°) typical of cruise operation at high altitude. Locating the inlets depends largely on the airframe, particularly the placement and arrangement of wings and tail surfaces. There may be one, two, or



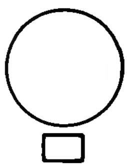
Four Axisymmetric Inlets



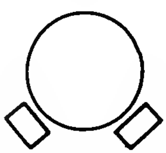
Two Axisymmetric Inlets



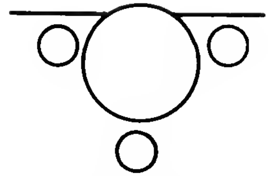
One Axisymmetric Inlet



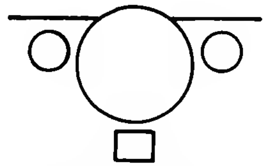
One Two-dimensional Inlet



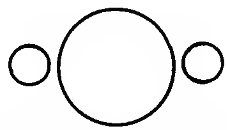
Two Two-dimensional Inlets



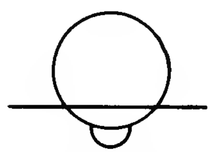
Two Axisymmetric Inlets Under Wing
and One Axisymmetric Inlet Under Body



Two Axisymmetric Inlets Under Wing
and One Two-dimensional Inlet Under Body



Two Axisymmetric Inlets Cheek-mounted

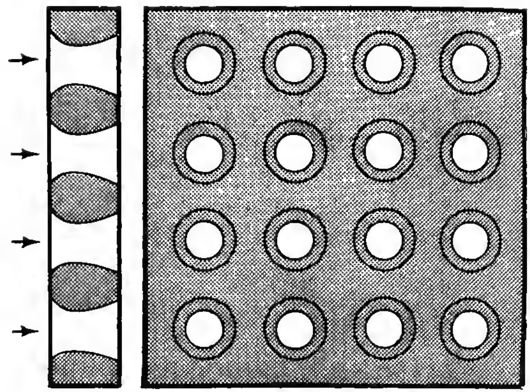


Half-axisymmetric Inlet Chin-mounted
Under Precompression Wing

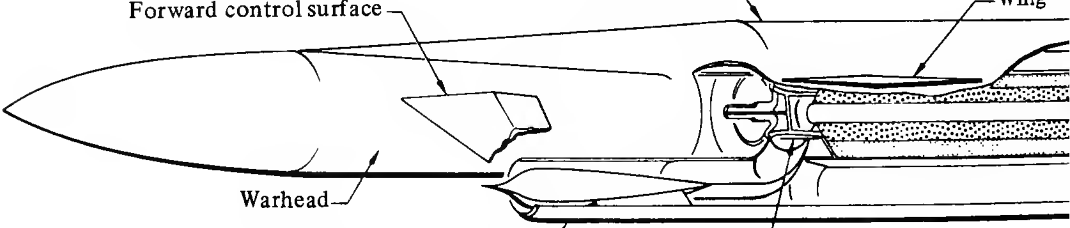
four inlets that are axisymmetric, half-axisymmetric, or two-dimensional. Different types of inlets may be used in multi-inlet configurations, especially in SFRJs where one or more separate inlets often supply bypass air to an aft or secondary mixer section of the combustor. Single inlets may be located on the bottom of the vehicle in the nose cone or body flow field (chin mount); dual inlets may be located on the sides (180° side mount or 90° cheek mount); four inlets may be in a cruciform arrangement. Generally inlets are located in line with tail or dorsal fins to minimize drag.

In LFRJs, after air leaves the diffuser it sometimes passes through the fuel tank by means of a transport duct of constant area. The air then flows into the turn and dump region of the combustor (where the fuel injectors and flameholders are located). If a flow-straightening device (an aerogrid) is required, it is located at the exit plane of the diffuser. Finally the air enters the forward section of the combustor.

In SFRJs, after air leaves the diffuser it passes through the turn and dump region of the inlet to the air injector system, which may incorporate flow straightening devices that improve flameholding. The air is then dumped into the forward end of the combustor.


Aerogrid for Square Diffuser Exit

Early ramjet vehicles such as Navajo, Bomarc, or Talos (all of which required a separate detachable rocket booster) placed inlet, combustor, and nozzle in a separate pod or nacelle attached to the main airframe, which contained the fuel tank. More recent design practice is to integrate the entire IRR into the vehicle body.



Example of Missile Powered

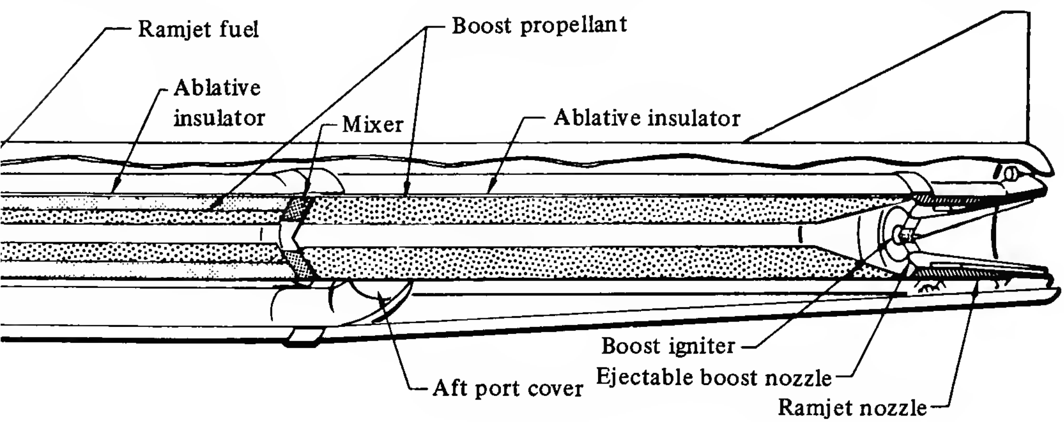
4

Fuel Management Systems

Fuel Delivery

It is convenient to subdivide liquid fuel management systems into two parts: fuel delivery and fuel control. The fuel delivery system supplies fuel from the storage tank by pumping or pressurization. A pump-fed system may be driven by any prime mover, but a gas turbine is often employed since the turbine is usually lighter than, say, an electric drive motor and batteries. Besides, batteries deteriorate in storage and must therefore be replaced periodically.

Gas for pressurized systems may be obtained by bleeding ram air from the inlet, or it may come from a high pressure storage vessel through suitable reducing valves. High pressure gas may also be produced when needed by combustion of liquid or solid fuel with air. An even better way, since it is independent of an air supply, is to generate the gas from a self-contained solid-propellant grain of suitable composition. When gas pressure is required, the solid grain is ignited and furnishes sufficient gas for the duty cycle of the ramjet. A system of this type is particularly advantageous for



d-fueled Integral Rocket Ramjet

applications where volume is limited and low cost is a dominant consideration. For example, certain chemical compositions developed by CSD can produce a larger volume of gaseous nitrogen from a given volume of solid than is obtainable from an equal volume of liquid nitrogen.

Ramjet-powered vehicles are subject to large acceleration forces during boost (say, zero to 1200 miles per hour in four seconds) and during flight maneuvers at high speed. It is therefore important to ensure that liquid fuel can be delivered from the tanks under any flight conditions. This requirement often means devising some sort of positive expulsion system so that the storage volume is continuously made smaller as the liquid is fed to the ramburner. In this way the storage volume is always just large enough to contain the remaining liquid so only liquid can enter the fuel line leading to the combustor. Accordingly, storage tanks are frequently equipped with collapsing or expanding bladders of soft metal or elastomeric materials. When gas pressure is applied to an expanding bladder system the bladder expands against the fluid, forcing it out of the tank. Conversely, the bladder may surround the fluid so that when it collapses (from exterior pressure), the fluid it contains is forced out. The challenge in designing a positive expulsion system is to ensure that the bladder expands or collapses predictably and without tearing, and that it empties the tank almost completely. CSD has developed and refined the technology employed in making positive expulsion systems that meet these requirements.

Fuel Control

Fuel control of a liquid-fueled IRR is a task whose complexity depends on the range of operating requirements to be met. Even for test stand conditions the requirements are sufficiently complex that preset controls are seldom usable. Pneumatic (open loop) controls can be used for relatively simple situations, but more complex missions usually dictate a more complex hydromechanical or electronic (closed loop) device. The fuel control system must match fuel flow with air flow so as to maintain fuel-to-air ratio within limiting values on both lean (blowout limit) and rich mixtures. Operation of the fuel control system is therefore closely interrelated with conditions in both inlet and combustor. In addition, the system must maintain an appropriate initial flow of fuel during the transition from rocket to ramjet operation, control inlet pressure margin, and limit flight Mach number.

Sometimes for special applications it is possible to simplify or eliminate some of these requirements. A simple feedback system can maintain thrust, speed, or combustor pressure constant for test stand operation or for sustained level flight. Or, for example, fuel flow might be preprogrammed during certain portions of the duty cycle of the propulsion system. However, for a flight profile that must respond to a wide range of maneuvering requirements some sort of adaptive control is necessary which senses pressure in the air induction system and receives commands and flight trajectory data from the vehicle guidance and control system.

A second level of complexity is reached with an adaptive control for flight at variable altitude or range to a fixed terminal target. Although altitude and speed change, there is no significant problem with large changes in angle of attack that affect inlet operation. Finally, the most complex adaptive control is needed to intercept a fast-moving, evasive target because angle of attack may now become a limiting parameter.

Operation of an LFRJ from sea level to altitudes greater than 60,000 feet will lead to air flow rates that vary by 10- to 15-fold. In addition, there will be required a twofold to fourfold variation in fuel flow at a given Mach number and altitude between a lean value for low-drag cruise and a rich value for acceleration and maneuver conditions. The fuel meter must therefore be designed to control fuel flow within, say, 5% over a 50-fold variation in total flow. This stringent requirement leads to a need for precise construction and close tolerances.

Measurements of input parameters for speed control may be obtained in a number of ways. For example, fuel rate may be set proportional to ram pressure, which is approximately proportional to the air rate near the design Mach number. Mach number may be determined from the ratio of ram pressure to static pressure. Adjusting ram pressure by correcting fuel flow causes the vehicle to achieve the desired Mach number. If velocity control is desired, a measurement of the total temperature may be used as a basis for converting Mach number to velocity.

Mechanical, hydraulic, or electronic systems may be employed to achieve the desired accuracy and quickness of response of the control system. The system must be designed to be insensitive to forces arising from rocket boost or flight maneuvers. It must take into account the possible effects of vehicle angle of attack on both sensing elements and control requirements. In addition, any possibility of unstable operation resulting from interaction between the combustor or the diffuser and the metering system must be prevented. Hamilton Standard Division has successfully adapted aircraft fuel control technology to ramjets.

5 Liquid-fueled Ramburners

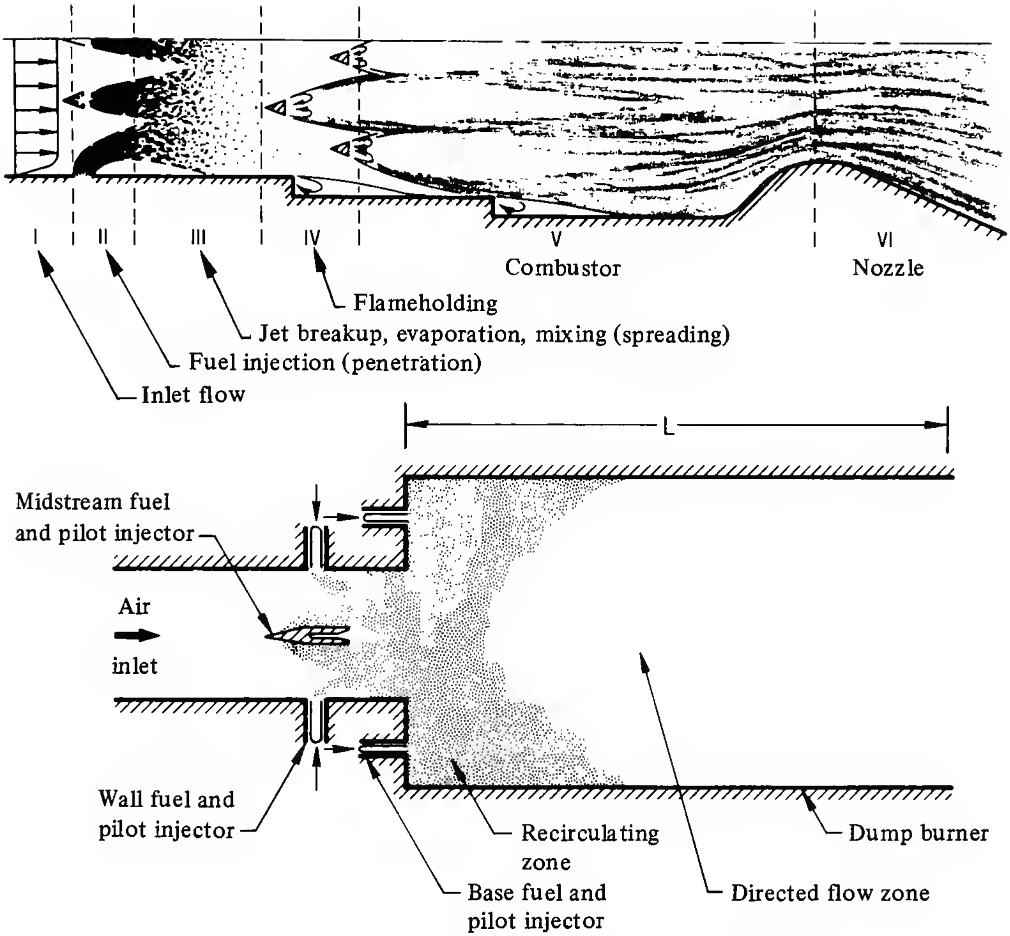
Another component requiring a high degree of skill in engineering design and analysis is the ramburner. Quite complex factors enter into securing high rates of heat release from the fuel with efficient combustion at all required altitudes and flight speeds. As an example, to minimize frontal area and drag, the velocity of the incoming air must be as high as possible. On the other hand, the air velocity at the entrance to the combustor must not exceed about 250 to 300 feet per second because of the complex interaction of aerodynamic factors and chemical kinetics.

The ramburner for an IRR includes the combustor, port covers, igniter, and thermal protection system. Engines for early ramjet vehicles such as Talos or Bomarc were installed in an external nacelle; in more recent vehicles the combustor is integrated with the vehicle body.

A so-called dump combustor is characterized by a rearward facing step or sudden expansion of the duct that creates a recirculation zone. Dump combustors may be concentric with the vehicle or side-mounted, depending on the overall vehicle arrangement.

Port covers seal the air inlets to the combustor during booster operation. Then they must be removed by one of several methods so that ram air can be admitted during the transition from booster to ramjet operation. The igniter is the device that starts combustion of the ramjet. The thermal protection system insulates the combustor and nozzle structure from the high temperature of the combustion gases.

The combustors for LFRJs and SFRJs are quite different because of their significantly different combustion processes and because the SFRJ combustor contains all of the fuel. The high velocity flow into the combustion zone of an LFRJ is accompanied by a high turbulence level as well as wakes, eddies, and recirculation zones generated by upstream spars, air intakes, and the like. These phenomena create problems of extreme complexity in devising straightforward design methods for fuel injection, vaporization, and controlled distribution. The problems are somewhat like those encountered in designing injectors for liquid propellant rocket engines, and must to a large degree be solved by educated cut-and-try

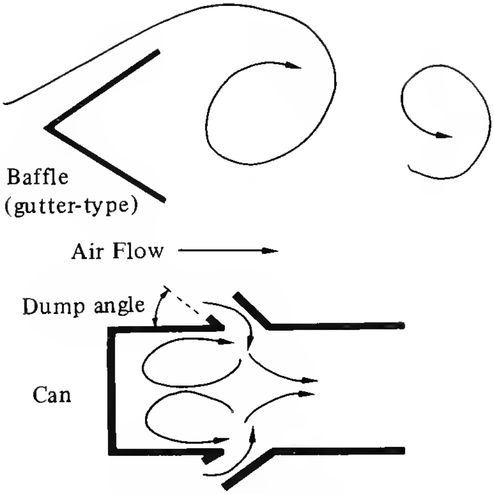


Fuel Injector and Flame Stabilization Processes in Ramjet Combustors

procedures. Most of these methods involve using an arbitrary number of fuel injection points (nozzles) and varying the geometrical arrangement and nozzle vaporization characteristics semi-empirically until a satisfactory fuel distribution pattern has been found. More quantitative methods can be applied in predicting the rate of fuel spreading from sources of various shapes in a turbulent stream and in predicting the degree of vaporization that will occur in a known time for a particular type of nozzle.

Flameholders

Early ramjet combustors encountered a major problem in maintaining a stable flame in the high velocity flow through the combustor (some 250 to 300 feet per second). The problem was solved by



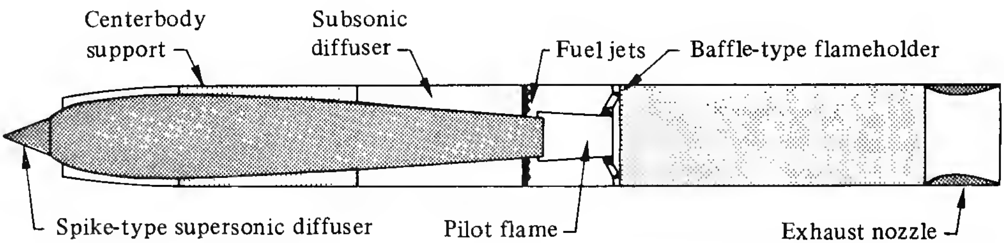
Flame Stabilizing Devices

introducing baffle flameholders in the duct. Behind these flameholders, recirculation zones were formed where the flow was sufficiently slow that a stable flame could be established. The same result was achieved by passing the inlet air to the combustor through holes or slots in a perforated plate or cone mounted in the duct. Combustors with the first type of flameholders have come to be called baffle-type combustors. The latter type is known as a "can" combustor.

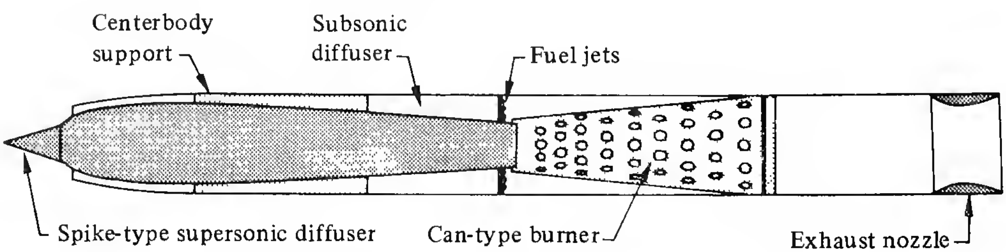
It was found quite early that a relationship exists between flameholder dimensions and flame blow-off velocity, and that blow-off velocity depends on the fuel-air ratio of the stream impinging on the baffle.

Heat Release Rate

With fuel distribution and stability limits defined in terms of combustor geometry and air flow, one further major



General Arrangement of Ramjet with Baffle-type Flameholder

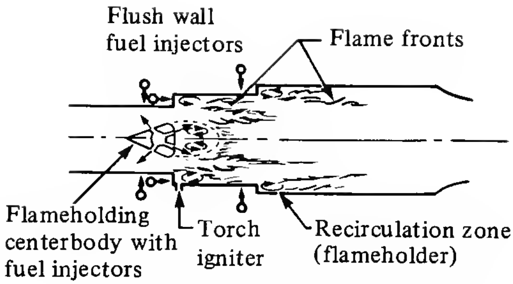


General Arrangement of Ramjet with Can-type Burner design criterion is needed to complete the requirements for combustor design. For a given cross-sectional area, heat release rate determines the length of combustor required to achieve a desired combustion efficiency.

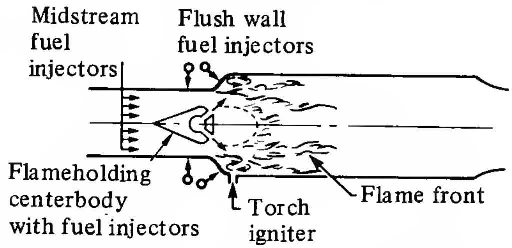
It turns out that the heat release rate for a baffle combustor depends on the rate (or angle) at which the flame spreads into the unburned material from the stabilizing baffles. The required combustor length is somewhat greater than the distance needed for the flame from one baffle to spread to the wall or to contact the flame spreading from another baffle. In a can combustor the unburned material enters the combustion zone in the form of jets that are gradually consumed. Here the "jet length" determines the required combustor length.

In effect, both baffles and cans may be thought of as devices to introduce sources of ignition from burned material into the entering combustible mixture. The rate of heat release thus depends on mixing rate and rate of combustion once an ignition source has been provided.

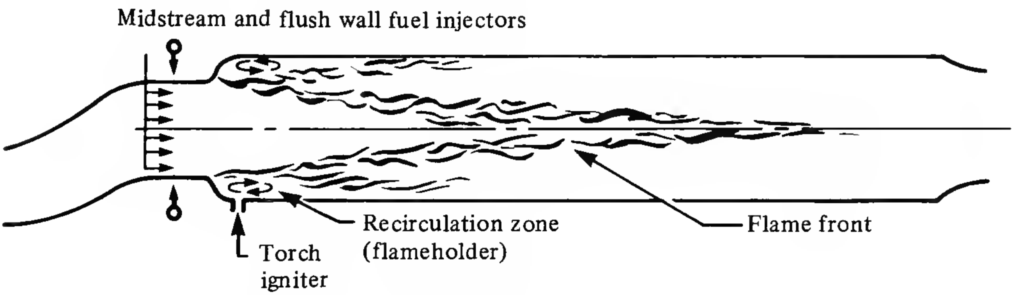
Ramburner performance and combustion instability have been shown to depend on inlet air temperature. At low altitude flight conditions, which generally occur at low Mach number, performance is decreased because of low inlet temperature and high air flow rates. This combination of conditions, when



Axisymmetric Multistep (Dual Dump) Combustor with Centerbody



Axisymmetric Combustor with Centerbody



Axisymmetric Combustor with Center Dump Inlet coupled with fuel that is injected under a low differential pressure, produces large fuel droplets with poor penetration, increases the difficulty of transporting the droplets into recirculation zones through gas turbulence, makes vaporization poorer, and causes incomplete mixing of fuel with air and nonuniform combustion.

Combustion Instability and Efficiency

Since the early days of ramjet engine development, combustion instability has been a problem of major concern. Unstable, periodic fluctuation of combustion chamber pressure that has been encountered in ramburners arises from several causes having to do with combustion mechanism, aerodynamic conditions, real or apparent shifts in fuel-to-air ratio or heat release, and acoustic resonance. From a physical standpoint the probable source of instability is the dynamic behavior of the recirculation zone. Both skill and ingenuity are needed to explain and correct combustion instability when it appears.

Aside from considerations of instability, the main concern in ramburner design is to achieve high performance. For IRRs, fuel distribution in the combustor (especially in the recirculation zones) and flameholder design have the greatest impact on performance. Obtaining high combustion efficiency at low overall fuel-to-air ratio requires high gas temperature within the recirculation zone. With both coaxial and side entry dump combustors, injecting fuel flush with the wall in the dump region will achieve this goal and at the same time improve flame stability limits. The only bad feature of this arrangement is that efficiency drops off as overall fuel-to-air ratio increases toward the stoichiometric value (that is, neither fuel-rich nor fuel-lean). Conversely, midstream injection gives high efficiency under stoichiometric conditions but flame stability limits are compromised. Therefore, some combination of injection sites often gives performance superior to either of these arrangements alone.

Port Covers

Port cover operation is a key element in the performance of an IRR. The cover (or covers) must withstand booster chamber pressures of 1,500 to 2,000 pounds per square inch without being ejected through the inlet. During the brief transition period after booster

STOICHIOMETRIC RATIO

The stoichiometric ratio is a proportion of chemical substances which is exactly correct for a specific chemical reaction, with no excess of any reactant. It is necessary to specify the reaction since the stoichiometric ratio is different if different products are formed. For example, methane burns with oxygen to form water and carbon dioxide or carbon monoxide. More oxygen is needed to form carbon dioxide from a given quantity of methane than to form carbon monoxide.

COMBUSTOR EQUIVALENCE RATIO

The ratio of actual to stoichiometric fuel-to-air ratio (often designated ϕ).

operation and before ramjet takeover, the cover must be ejected reproducibly, reliably, and without damage to the combustor or nozzle thermal protection system. It would be desirable if the port cover were self-ejecting under ram air pressure. Then, as the booster chamber pressure decayed to zero, the cover would be ejected automatically without the need for any other mechanical device.

Both monolithic and segmented port covers have been employed successfully. However, several newer concepts are of considerable interest because they offer the possibility of reducing the size of ejected pieces or eliminating them entirely. One approach is to mechanize the port cover, so that it can be opened without being ejected. For example, the cover could be hinged, louvered, or sliding. In each case an actuating device would be needed. These approaches would be particularly good for small dump openings. Moreover, the port structural elements would create recirculation zones that would act as flameholders.

Another approach is to make the port cover from high strength chemically treated or heat treated frangible glass. When the glass is broken (by a hard metallic pin that penetrates the hard outer surface or by a small detonating device) it breaks into granules shaped like rock salt and about the size of the original glass thickness. This method seems best suited for combustors with center dump.

Still another idea is to employ a consumable cover consisting of a support grid plate covered with a layer of solid propellant reinforced with metal screening. After the propellant burns away, ram air flow consumes or ejects the screen while the grid remains in place. The grid could be arranged to act as a flameholder.

Igniter

The igniter for a liquid-fueled IRR is usually a one-shot pyrotechnic type which is actuated briefly during ramjet takeover. In early ramjets continuous ignition was necessary to attain high efficiency or to prevent blowout at lean fuel-to-air ratios.

Thermal Protection System

The thermal protection system maintains the combustor and the nozzle below their maximum allowable temperatures. For moderate heat loads (Mach number less than 2.5) and relatively short durations, air cooling, film cooling, and radiation cooling techniques are adequate, although most of them add some complexity, cost, or weight. The preferred technique is ablative cooling, whereby the surface layers of the protective material are charred and vaporized. In this way they absorb the heat of the combustion gases and keep it from the structure being protected. Suitable ablative materials include inorganic oxides such as silica, magnesia, or asbestos in phenolic, epoxy, or silicone elastomers.

These materials char at accurately known rates that depend on temperature and velocity of the hot gas, so they are easily applied to a particular duty cycle by adjusting their thickness. The main considerations in using these materials are to ensure that the booster grain is securely bonded to the ablator and to retain the charred ablator in the combustor throughout the ramjet duty cycle. These requirements are not always easy to meet, since the best ablators tend not to bond to propellant very well, and after they have become charred they tend not to remain attached to the combustor wall. The usual techniques for dealing with these problems are to coat the ablator with some material that bonds well to both the ablator and the booster propellant or to retain the ablator in the combustor by means of some mechanical device.

The maximum temperature of a component protected by an ablative material during long cruise missions is a function of the thermal conductivity of the fully charred ablative, the char thickness, and the effect of external aerodynamic heating resulting from cruise conditions. After all vaporizable material of the ablator has been driven off, decomposition in depth of the ablator is complete. Only the char remains, and the thermal conductivity of the char is the only property that affects the temperature gradient through it. Predicting the thermal conductivity of char accurately at high temperature is therefore of utmost importance.

Nozzle

The nozzle is often considered to be part of the combustor, possibly because it is often convenient to manufacture the two components as part of the same assembly. Most ramjet nozzles have a fixed throat area. It is possible to devise two-position nozzles so as to optimize ramjet performance for two different thrust levels. It is even possible to design continuously variable nozzles that can optimize performance at all flight conditions. In practice, however, the complexity and added weight of such nozzles as well as the impact on the rest of the propulsion system rarely justify these approaches.

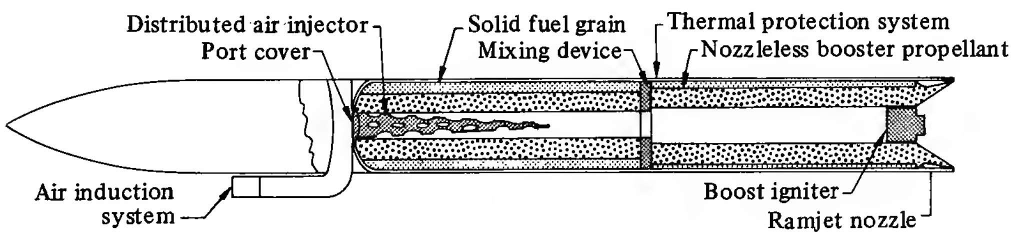
6

Solid-fueled Ramburners

Ramburners for SFRJs include some components not present in their liquid-fueled counterparts: solid fuel grain, air injector, mixer, and bypass. (They also do away with fuel control and delivery systems.) In discussing these components it is important to recognize that there are two basic combustor configurations for SFRJs. In the nonbypass arrangement all of the air from the inlets passes through the port (the open passage that runs the length of the fuel grain). In the bypass configuration a significant portion of the inlet air is admitted downstream of the fuel.

Nonbypass Configuration

The nonbypass configuration is lower cost and uses simpler metal parts, primarily because of the simpler interface between combustor and inlets. But there are two disadvantages. First, to stabilize combustion there must be a rear-facing step of suitable height to obtain recirculation zones and the gas velocity (or Mach number) within the fuel grain port must be limited. These requirements (which in effect set the flameholding conditions) are defined in terms of a critical step height (or port-to-injector area ratio) and a maximum allowable port Mach number. In practical system designs these requirements often impose an unacceptable limit on the amount of fuel that can be carried. Moreover, at higher ramjet thrust levels the combustor nozzle throat area must be a larger fraction of the combustor area (which is usually fixed by the vehicle design), so the



Nonbypass-type, Solid-fueled Integral Rocket Ramjet fuel port area must be further enlarged to keep the port Mach number below its allowable limit. Enlarging the port area further reduces the amount of fuel that can be contained within the combustor.

The second disadvantage of the nonbypass configuration is its tendency to low combustion efficiency, mainly because of incomplete mixing of air and fuel gas within the combustion chamber. Efficiency can be improved by incorporating mixing devices in the combustion chamber or in a mixing section downstream of the fuel grain.

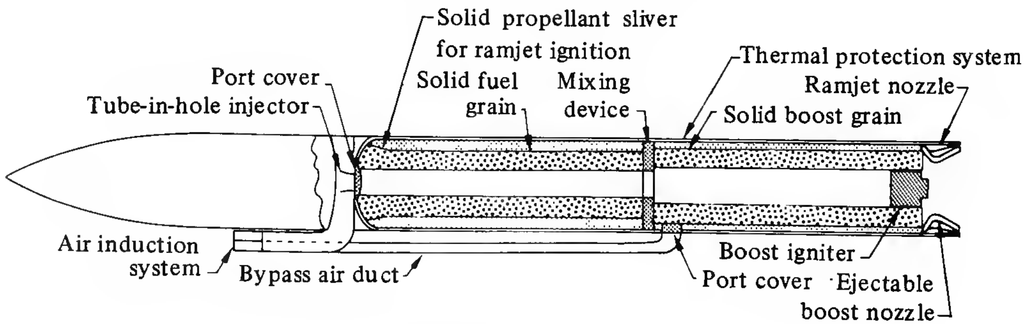
Bypass Configuration

The alternate approach to combustors is to bypass a portion of the captured air and inject it downstream of the fuel grain directly into the mixing chamber. This method greatly improves combustion efficiency and has another effect that is even more beneficial. Since not all of the air passes through the fuel grain port, the port area can be reduced without causing the air flow to exceed the allowable Mach number. The reduced port area increases the fuel load. Because of the dual effect on combustion efficiency and fuel load, overall performance of the bypass engine can be considerably greater than the nonbypass.

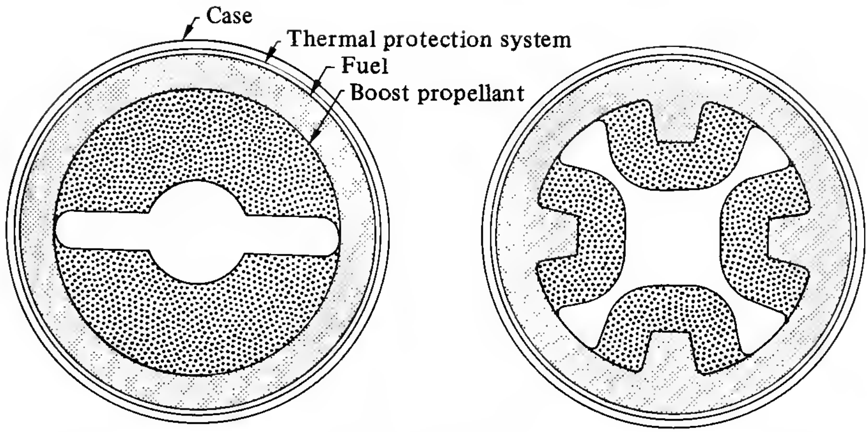
It must be emphasized that for certain applications the thrust requirements are not high enough for limiting fuel load to be the deciding factor on overall vehicle performance. The primary consideration in selecting a configuration is often combustion efficiency rather than fuel load. In one application for a low thrust engine, for example, preliminary calculations showed that a bypass engine offered 27% greater range than a nonbypass engine. However, 20% of this difference was attributable to lower combustion efficiency and only 7% to limiting fuel load. For this application, therefore, the nonbypass engine could compete quite effectively if its combustion efficiency could be improved.

Fuel Grain

Fuel grains for solid-fueled IRRs almost always have a perforation that runs the length of the grain to permit inlet



Bypass-type, Solid-fueled, Integral Rocket Ramjet



Boost/Fuel Grains with Stress Relief

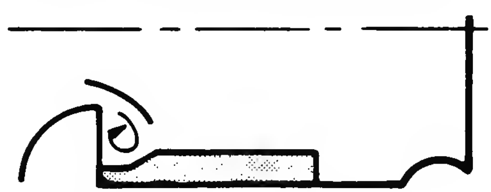
air to flow through it. Although an end-burning grain could be employed (as in a ducted rocket, which was described earlier), practical considerations essentially dictate a fuel grain with a round hole or one with spokes of some sort extending into the port.

In the IRR, the boost propellant grain is in the same combustion chamber as the sustain fuel. Like a conventional solid propellant, the boost propellant contains its own oxygen for combustion. However, the fuel grain for the sustain portion of IRR operation requires oxygen from the atmosphere. Although for some applications it may be appropriate to have a small percentage of an oxidizing material mixed with the fuel, the amount is insufficient to sustain combustion in the absence of atmospheric oxygen.

Flameholding

The basis for all modern developments of SFRJs has been the ability to stabilize flames by means of a rearward facing step located at the forward end of the fuel grain. The energy released by combustion occurring in the recirculation zone downstream of the step sets up conditions that propagate the flame down the remainder of the fuel grain.

There are two parameters that affect flameholding. The first, called the injector area ratio, is the ratio of the fuel port area to the area of the air injector. An equivalent parameter of more physical significance is the ratio of the height of the rearward facing step to the fuel port diameter. Either of these terms can be used so long as it is remembered that the blockage area must be adjacent to the fuel grain if combustion is to be



Rearward Facing Step with
Controlled Recirculation Zone

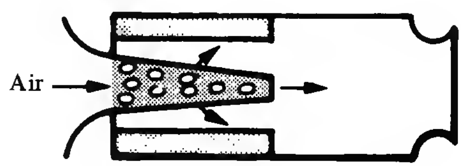
sustained in the recirculation zone. The second parameter that affects flameholding is the velocity (Mach number) in the fuel grain port. It has been found that the injector area ratio must be greater than some critical value, otherwise flameholding cannot be achieved at any Mach number in the fuel grain port. If this ratio is greater than the critical value, combustion can be stabilized over a range of port Mach number up to some limiting value. However, if the port number exceeds the limiting value, blowoff will occur in any case.

Two techniques have been developed to improve the capability of the step flameholder, which causes turbulent and distorted air flow. The first is to inject air directly into the recirculation zone to intensify the heat release there, since the combustible mixture in the recirculation zone is fuel-rich. The second, which is a little simpler in practice, is to use a so-called tube-in-hole injector. Here the annular sleeve in the combustor inlet smooths inlet flow and proportions the air for entrainment into the flameholder recirculation zone.

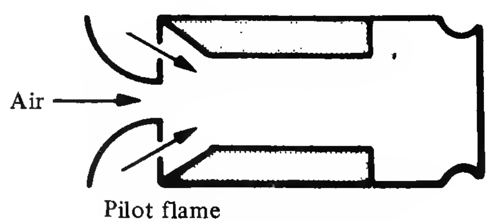
Combustion Efficiency

Left to itself, the gas near the fuel grain surface is fuel-rich and that near the center of the port is air-rich. Unless this difference is equalized, combustion efficiency will be poor. In the nonbypass engine configuration, mixing is promoted by a vaned mixer located immediately downstream of the fuel grain. The enhanced mixing dramatically improves combustion efficiency. The bypass engine gives excellent combustion efficiency more easily than the nonbypass configuration because the bypassed air is admitted at right angles to the fuel-rich combustion gas stream. This arrangement in combination with a simple mixer plate with orifices gives quite efficient mixing (as well as natural secondary flame stabilization) under all conditions, yielding high combustion efficiency.

The bypass engine also offers the potential for throttling a solid-fueled ramjet by varying the fraction of the air that passes through the fuel grain port. The fuel flow rate changes with the fuel regression rate ("burning rate"), which can in turn be varied by changing the air mass flow rate through the fuel grain port. Thus, a simple damper in the bypass duct can change the air bypass ratio and therefore the fuel flow rate.



Distributed Air Admission



Pilot-stabilized Combustion

7 Boosters

The booster portion of an integral rocket ramjet must (1) accelerate and launch the vehicle to ramjet takeover velocity, (2) provide high volumetric loading (fill the available space with as much propellant as possible), (3) accommodate center of gravity requirements dictated by the guidance and control system, (4) survive the severe air launch environment, including vibration and exposure to temperatures ranging from -65 F to 165 F, (5) and end its boost phase with a reasonably sharp and reproducible pressure decay for reliable ramjet takeover.

Booster Grain

Booster propellants that can meet these requirements are quite similar to ones used in solid propellant rockets. For a liquid-fueled IRR, the booster grain is cast in the combustor. When the booster grain has burned, the inlet port covers are opened and transition to ramjet operation occurs. For a solid-fueled IRR, the booster grain may be cast as an inner layer over the sustainer fuel grain, in the combustor volume downstream of the mixer (where there is no fuel grain), or in both places.

A rather effective refinement is to remove a "sliver" of the fuel grain from a recess at the forward end of the combustor and fill the vacated space with booster propellant. When the bulk of the booster propellant has been consumed, the sliver of booster propellant burns long enough to ignite the air-fuel mixture at the onset of ramjet takeover. One to two seconds of additional burning usually can be provided after the rest of the propellant has been consumed, and this interval is adequate for reliable ignition. One reason this method works is that during transition the chamber pressure falls rapidly (since it is not being maintained by the main portion of the booster grain, which has been consumed). When the pressure decreases, the burning rate of the sliver is diminished also. The burning surface of the sliver is sized so that the pressure it can supply by itself is an insignificant percentage of the expected sustainer pressure.

Locating the sliver in the recirculation zone is ideal for other reasons. First, the air flow is entrained in the sliver flame and swept over the fuel surface, which is heated very effectively. Second, in the recirculation zone the regression rate of the sustainer grain tends to be lower than for the remainder of the fuel. By replacing this part of the fuel grain with booster propellant the difference in regression rate can be partially compensated for. Third, the larger effective volume of the recirculation zone can lower the recirculation velocities and improve flameholder stability.

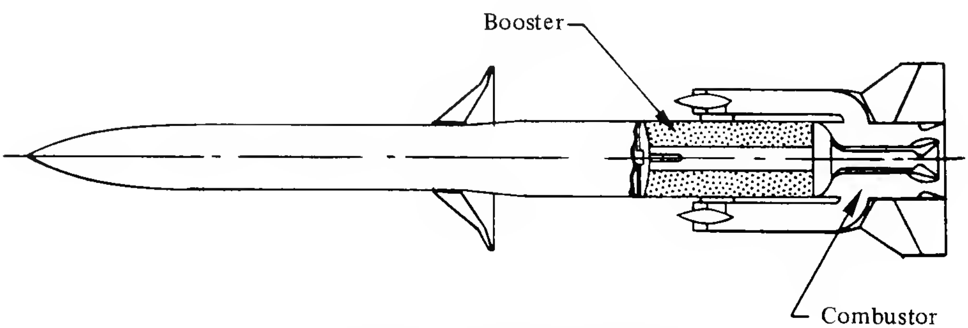
Nozzle

The nozzle for the booster has a smaller throat diameter than the nozzle for the sustainer. The reason for the difference is that the booster operates at a chamber pressure of 1000 to 2000 pounds per square inch whereas the sustainer operates at less than 100 pounds per square inch. One way to meet these differing requirements is to eject the booster nozzle at the end of booster operation. A disadvantage is that large fragments ejected from the engine might damage the vehicle or its launching platform.

To eliminate this disadvantage and to lower propulsion system cost, some alternative nozzle concepts can be considered. The idea of using a submerged nozzle leads to some rather interesting variations of the basic IRR. As defined for airbreathing propulsion system applications, a submerged nozzle is located on the main missile axis but forward of the aft plane of the missile. Being on the main missile axis, the submerged nozzle must dump its supersonic exhaust products through the aft portion of the combustor chamber and the ramjet nozzle. The submerged nozzle makes possible some propulsion systems that are lower cost or may have advantages in certain situations over the standard IRR.

Tandem Rocket Ramjet

The tandem rocket ramjet (not to be confused with a ramjet having a separate, detachable booster) offers cost advantages for some applications because some of the complexities of the transition sequence are eliminated. In this arrangement the booster grain is forward of the sustain combustor. The



Tandem Rocket Ramjet with Submerged Nozzle exhaust gases from the booster travel through a blast tube and exit through the booster nozzle, which is located inside the ramjet nozzle. At booster exhaustion, ramjet takeover occurs as liquid fuel is injected into the aft-located combustor. The ramjet exhaust gases escape through the annulus formed by the ramjet and booster nozzles. While this arrangement avoids the problems associated with port covers, it presents the difficult task of developing the blast tube.

Nozzleless Booster

A concept advanced by CSD that may lead to lower cost propulsion systems is the nozzleless booster. The reason is that for virtually all solid rockets the nozzle turns out to be the most costly single component. The expense is caused partly by the need for expensive materials that can withstand high temperature and high velocity at the nozzle throat. Other materials, usually ablative, are employed for exit cones. In addition, the nozzle's design and construction are complex. The temperature-resistant materials must be artfully reinforced with structural members that hold the nozzle assembly together under high internal pressure.

At first thought it might seem that removing the nozzle would cause so great a loss in performance that this approach would be impractical. There is a loss of specific impulse from the normal 245 to 250 seconds to around 200 seconds, or some 20%. However, the space formerly occupied by the nozzle can be filled with additional propellant, reducing the performance decrement. Moreover, the cost of mixing a slightly larger batch of propellant is merely the cost of the ingredients. The propellant ingredients at less than a dollar per pound are far cheaper than a nozzle at perhaps $100 per pound. Overall, a nozzleless booster costs 20% to 40% less than one with a nozzle.

A significant advantage of the nozzleless booster in the integral rocket ramjet is that it completely avoids the complexity associated with ejecting the booster nozzle. The ramjet nozzle, however, is retained and contributes a small improvement to booster performance. To derive the greatest benefit from a nozzleless booster it is necessary for the propellant properties to be tailored to the application. Generally such a propellant requires as low a pressure exponent as possible and a higher burning rate, density, and specific impulse than conventional rocket propellants.

8 Ramjet Testing

When a flight propulsion system is designed to operate close to its limits of strength it must be tested extensively before committing it to a flight vehicle. Ground testing of such a system can never be a perfect substitute for flight testing but it is the next best thing because, carefully done, it can uncover most of the potentially severe problems of the system. Moreover, it is generally possible to start ground testing before the flight vehicle is available, and results of ground tests can often influence vehicle design.

In testing a ramjet at sea level it is important to reproduce as closely as possible the conditions that the engine will encounter in flight. Three main test methods are used: freejet, semi-freejet, and connected pipe.

Freejet Testing

Freejet testing involves producing a stream of air at the pressure, temperature, and Mach number corresponding to the flight condition and of sufficient size to encompass the whole engine. Only in this way is it possible to reproduce the flow conditions around the engine and determine its overall performance.

It is important to ensure that no reflected shocks from the facility or the model disturb the flowfields approaching the air induction system. When the inlet is near the nose cone of the vehicle, the disturbances from reflected shocks are negligible. However, aft-mounted inlets must be shielded from reflected shocks by a jet stretcher. Often it is difficult to simulate the flow field at high angle of attack; in addition, angle-of-attack simulation itself may be limited by the relative sizes of model and facility.

Freejet testing is generally expensive because of the size and complexity of the facility, the large mass flow rates of conditioned air that are needed, and the specialized test equipment that is necessary. However, essentially all pertinent flow fields can be accurately simulated. This feature is important to propulsion system performance, particularly when the air induction system is closely adjusted to the local flowfield.

Connected Pipe Testing

Connected pipe tests are adequate for trying the combustion system, since the combustion process is not affected by flow outside the engine. In these tests, air at conditions corresponding to those leaving the intake diffuser is fed directly to the combustion system.

Semi-freejet Testing

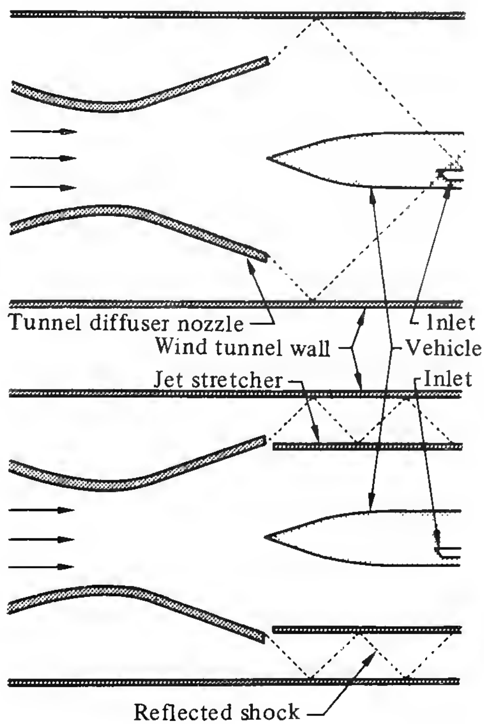
Semi-freejet testing of ramjet engines is a relatively new technique that reduces cost compared to classical freejet testing. This technique is particularly useful for testing IRRs since it can demonstrate real time transition from rocket booster firing as well as ramjet performance at specific altitude and Mach number conditions or over full flight trajectory using simulated external aerodynamic heating.

The basic approach in semi-freejet testing is to subject the air induction system alone to the freejet environment rather than the entire integrated vehicle. Its main deficiency is that the air induction system (and, consequently, the propulsion system) is not being influenced by local flowfield effects. For configurations with inlets located far back on the vehicle body the impact is small, since flow conditions at the inlets are nearly the same as freestream at zero degrees angle of attack. On the other hand, inlets located forward on the vehicle body are in a region where the flow is less uniform. The reason for the nonuniformity is the greater influence of forebody shock and its accompanying flowfield. As a result, angle of attack is limited to lower values in semi-freejet than freejet testing.

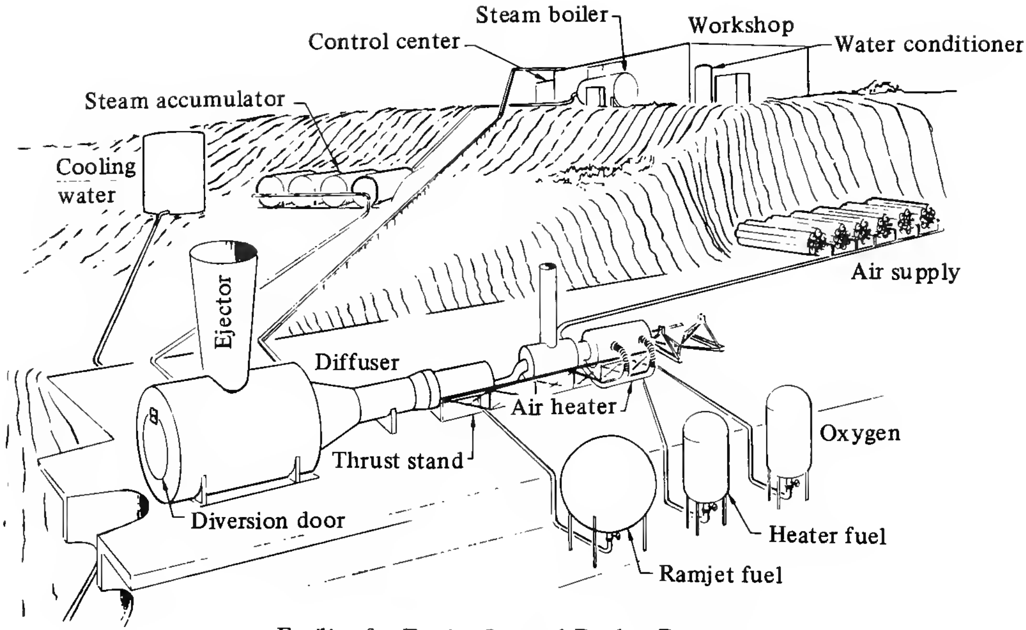
Testing IRRs adds one further complication since the rocket booster nozzle must be expelled as part of the transition to ramjet operation. The test facility must provide some sort of door through which the ejected nozzle can pass and which can then be closed to maintain altitude conditions for the ramjet phase of operation.

Aerodynamic Heating

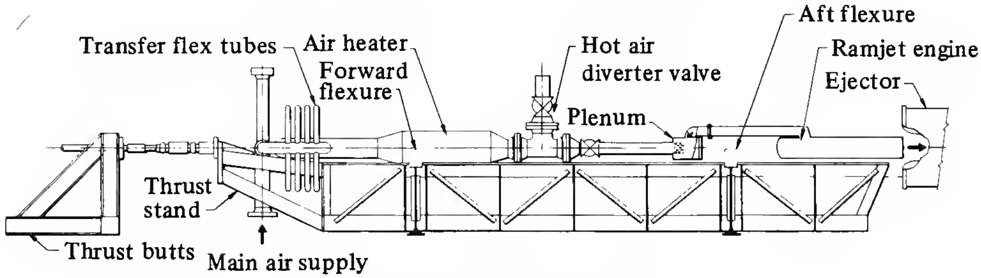
At the high Mach numbers typical of ramjet operation, aerodynamic heating can be a significant factor. Valid freejet and semi-freejet tests must therefore be further complicated by some means of imposing aerodynamic heat loads to the



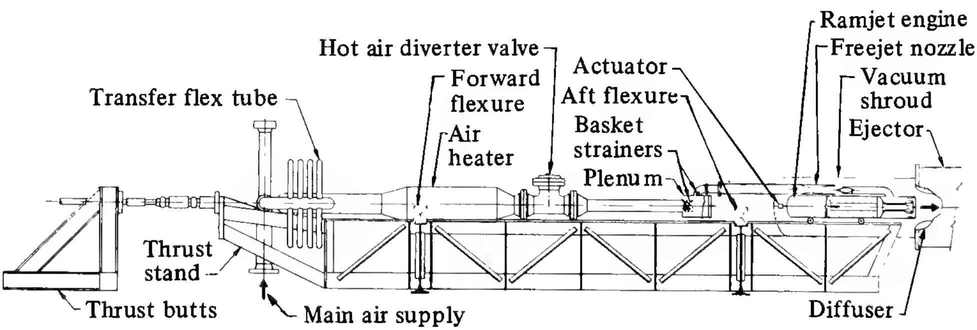
Use of Jet Stretcher to Shield Inlet from Reflected Shock Waves



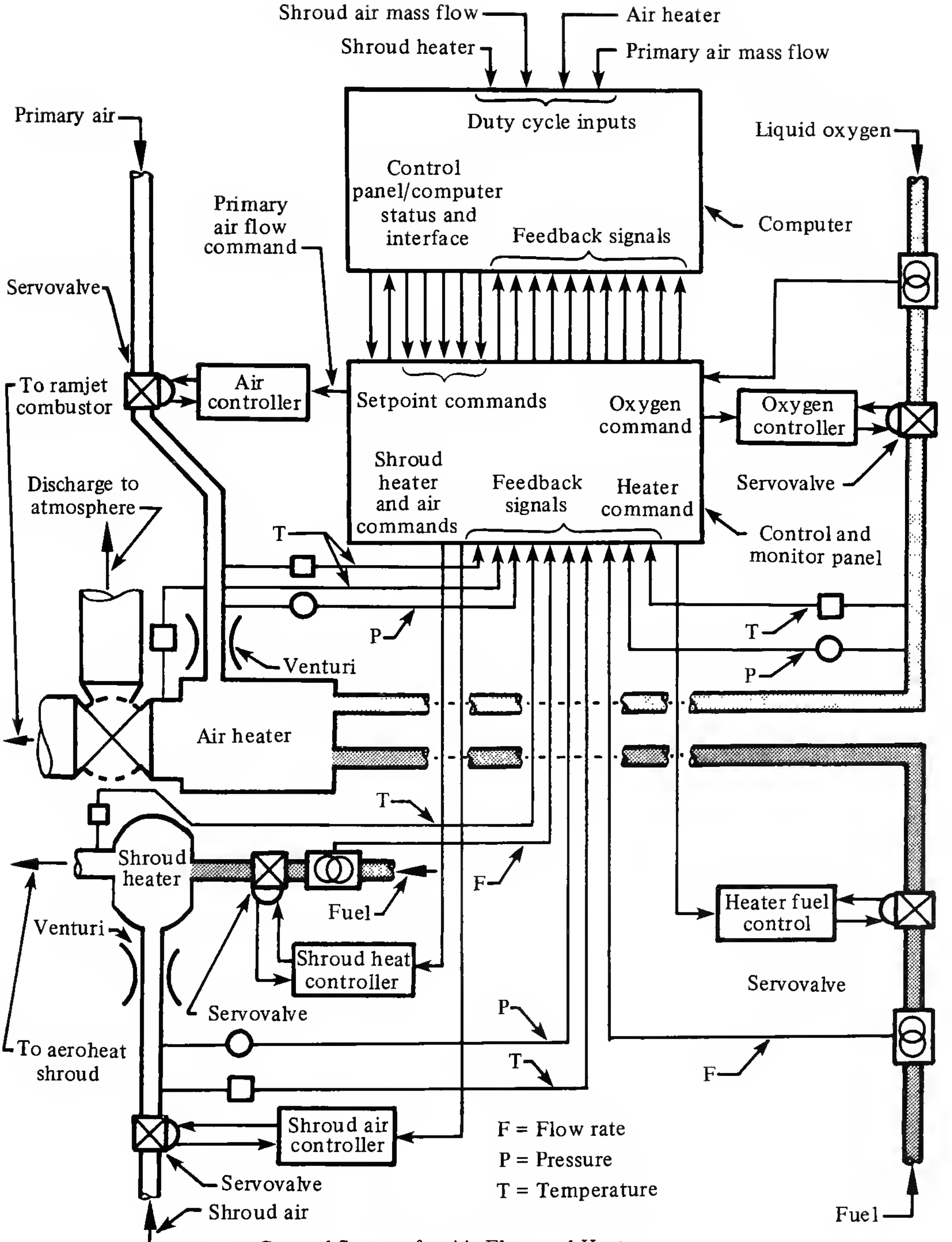
Facility for Testing Integral Rocket Ramjets



Direct-connect Ramjet Facility



Semi-freejet Ramjet Facility



Control System for Air Flow and Heaters

ramjet which match the flight Mach number experienced by the inlet. In practice a separate stream of heated air is supplied to a shroud surrounding the engine. The temperature and mass flow rate of shroud air must be continuously determined and controlled to match the operating conditions at the inlet.

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Applications for Integral Rocket Ramjets

Generally speaking, IRRs are superior in performance to boost/sustain rockets when the ratio of sustain to boost impulse is favorable. As a rule of thumb, IRRs are better if less than about 70% of the total impulse (thrust times duration) of the system is required for boost. The characteristics of IRRs make them particularly suitable for (1) extended range tactical weapons, (2) powered intercept at longer ranges (for engaging maneuvering targets), (3) replacing existing volume-limited rockets with a propulsion system having much higher performance, and (4) extended range ordnance against high-speed ground targets.

Ramjets are favored over other power plants in applications in which (1) appreciable range is required at speeds greater than Mach 2, (2) engine weight or drag is a significant fraction of the weight or drag of the vehicle, (3) engine cost is of major importance, and (4) the available volume is insufficient for a rocket motor because of its significantly lower performance. IRRs make auxiliary boost unnecessary and therefore remove a primary disadvantage of the pure ramjet. It is worthwhile to discuss briefly a few of the applications in which IRRs are a pre-eminent choice.

Antiaircraft Guided Missile

High speed and long range capabilities are required in antiaircraft guided missiles designed to cope with high speed bomber or fighter attacks. High thrust per unit frontal area is important in minimizing drag and reduces volume requirements in missile-firing installations. The ramjet's need for rocket boost makes it possible to attain cruising speed quickly and reduces the range of minimum engagement and time to target. Specific fuel consumption is not of primary importance (except for volume-limited applications), but values as high as those typical of rockets cannot be tolerated for ranges greater than about 30 miles. The simplicity and low cost of the IRR as well as its outstanding performance at high speeds make it a prime choice for this application.

Target Drones and Remotely Piloted Vehicles

In target drones, low cost of the power

plant is of primary importance. The comparatively simple construction of the IRR offers significant advantages for this application.

The greater efficiency of the ramjet at high speeds gives it an advantage for remotely piloted vehicles requiring long range with cruise speeds above Mach 2. It is clear that the need for increasingly longer standoff distances will call for higher and higher attack speeds. With progress in automatic control and target identification techniques the emergence of the IRR as the favored propulsion system for remotely piloted vehicles seems assured.

Tactical Missiles

The characteristics of various IRR propulsion systems can be compared in terms of the applicability of several such systems to a wide range of tactical missiles. In a rather comprehensive study it was found for weight- and volume-limited missiles that the liquid-fueled IRR can contain the maximum total impulse. It therefore gives the highest performance, especially for missiles that must operate over a wide range of altitude and Mach number. The ability to control fuel flow to match performance requirements is a distinct benefit. On the other hand, where velocity alone is the dominant factor, as for example in intercepting a maneuvering target, the performance advantage of the liquid-fueled IRR is reduced.

Although the solid-fueled IRR offers good performance it provides only a partial form of fuel control and it does not maintain fuel-to-air ratio at optimum levels over a large range of altitudes. It is most applicable, therefore, to missions that do not demand a large change in operating altitude.

The ducted rocket shows its best relative performance in smaller class vehicles where the operating envelope is reasonably limited. The high fuel density of the ducted rocket makes it attractive in volume-limited systems. However, since its fuel is expended at essentially constant rate it is penalized if operation is required over a large range of altitudes.

Cruise Missiles

Another useful comparison can be made for cruise missiles. Here the ramjet offers the advantages of low volume and best performance at high altitude (70,000 to 90,000 feet) and high Mach number (3.5 to. 4.5). Its disadvantages are that it cannot match the long range capability of the turbojet if subsonic cruise at low altitude is adequate to meet mission requirements. Moreover, to achieve long range the ramjet must cruise at high altitude and high speed, so it needs a small radar cross-section if it is to penetrate defensive screens defensively.

The SFRJ offers the desirable operational and storage features of a solid rocket (low cost, simplicity, and high reliability, with minimum handling and support equipment). It offers greater range than boost-sustain, dual chamber, or pulsed solid rockets. However, the solid fuel grain limits a multiple mission envelope (many Mach numbers and altitudes). Like the LFRJ, it must cruise at high altitude and high speed to obtain long range.

Podded ramjets have for many years been in the military inventory. The Navajo intercontinental missile employed a podded ramjet, but the program was cancelled during development. The Navy's Talos (surface-to-air missile) became operational in 1959 and is scheduled to be phased out in the 1980s. The Air Force's Bomarc (also a surface-to-air missile) was developed in the mid-1950s and is still operational, as is the Army's Redhead Roadrunner, a supersonic high or low altitude target drone. The podded LFRJ is the simplest and therefore the lowest cost ramjet system (remembering that an auxiliary booster must be supplied to make the ramjet work). The principal disadvantage is large total volume compared to an IRR, with higher drag during boost.

A number of cruise-type missiles have relied on low-cost turbojet engines for propulsion. In 1953 the Matador, a surface-to-surface missile, became operational. Within the ensuing 10 years the Snark, Mace, Quail and Scad (decoys), and Hound Dog (air-to-surface missile) were deployed. The Harpoon and the air-launched cruise missile are under development. The advantage of the turbojet engine for these applications (aside from its established technology) is that it gives the highest specific range per pound of any propulsion system. Against this considerable advantage must be weighed a number of significant disadvantages. Turbojet thrust is limited compared to ramjets or rockets. Turbojets cost more than competitive systems and are essentially limited to operation below Mach 2. Moreover, turbojets have lower thrust per pound and lower thrust per unit cross-sectional area than ramjets or rockets.

Cost

In any propulsion application, aside from strictly technical considerations of operating and performance characteristics there inevitably arises the question of cost. It is not uncommon for a particular propulsion system to meet technical requirements with flying colors only to be rejected because of unacceptably high costs. Therefore, some cost comparisons with other propulsion systems are in order. Comparisons with rocket engines are not given since for most of the applications of interest a rocket will not meet the requirements unless its size, weight, or complexity increase to unacceptable values.

Turbojet engines are now employed for drones and other pilotless vehicles that could be powered by integral rocket ramjets. Based on 1976 figures, a turbojet engine costs \$40 to \$70 per pound of thrust. Liquid-fueled IRRs for the same missions would cost \$8 to \$15 per pound of thrust. Solid-fueled IRRs would cost \$5 to \$10 per pound of thrust. The arguments in favor of the IRR are thus fully justified when cost is made a deciding parameter.

10 CSD, a Leader in Ramjet Propulsion

In 1972 the management of United Technologies recognized the growing need for ramjet propulsion systems in the nation's arsenal and resolved to take advantage of existing technological skills held within the corporation, combine these skills, and compete for ramjet propulsion programs. In carrying out this

CSD's Sunnyvale Center

CSD's Semi-freejet Facility at Coyote Center

resolve UTC assigned its Chemical Systems Division the responsibility of leading the corporate effort with major support from United Technologies Research Center and the Hamilton Standard Division.

To carry out its ramjet work, CSD expanded its existing test facilities to provide the capability for semi-freejet testing of integral rocket ramjets. Unique in the industry, this test facility is designed specifically to test booster operation, transition, and subsequent ramjet operating modes in one sequence under both sea-level and simulated high-altitude conditions. The fully automated facility, located at the division's Coyote Center, can handle up to 1000 pounds of solid propellant. Ramjet trajectories can be simulated through computer control of altitude, fuel and airflow rates, and air total temperature, including the effects on structures of aerodynamic heating.

The large scale facilities at Coyote Center, which include capability for hardware manufacturing, are supported by research-scale installations at CSD's Sunnyvale Center. In addition, Hamilton Standard Division has extensive facilities for developing, testing, and manufacturing fuel control systems. United Technologies Research Center is generously provided with facilities for testing air induction systems and was first to prove an integral rocket ramjet in flight.

The combination of highly qualified staff from all three organizations, comprehensive and specialized facilities for developing, testing, and manufacturing all components of integral rocket ramjets, and CSD as a system-oriented lead organization represents a powerful team for meeting the nation's growing need for ramjet propulsion systems.

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NOTES

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