WILLIAM B. SHIPPEN, WALTER G. BERL, WILLIAM GARTEN, JR., and
EVERETT J. HARDGRAVE, JR.

THE TALOS PROPULSION SYSTEM

Development of the ramjet engine for Talos required the solution of many new engineering problems, including maintenance of stable engine operation at high as well as low altitudes; assurance of engine durability during long periods of high-temperature operation; maintenance of stable and efficient intake performance; and provision of a fuel system that would store, pump, distribute, and control the fuel rate.

In January 1945, APL was authorized by the Navy Bureau of Ordnance to commence basic and applied research in support of the development of a guided missile. Until that time, no ramjet-powered flights were known to have taken place, even though the basic idea for the ramjet had been enunciated by René Lorin of France as early as 1913. Intelligence reports of German activities during World War II, and captured documents as well, showed that ramjet engines had been developed for subsonic and supersonic flights, but no applications were made.

The ramjet engine is similar in principle to the turbojet but relies completely on its forward velocity to supply high-pressure air for the combustion chamber. It is not self-starting and requires a rocket booster for acceleration to the minimum operable flight velocity at which it develops sufficient thrust to maintain flight speed or accelerate further. The major components of the ramjet (Fig. 1) are: (a) an air inlet, designed to capture the desired amount of air at supersonic speeds and convert its dynamic pressure to a high static pressure at low velocity for subsonic combustion; (b) a fuel system that provides and controls the fuel flow; (c) a combustion chamber, where heat is added by burning the fuel; and (d) an exit nozzle, where the heated products of combustion are increased in velocity and expanded to ambient pressure.

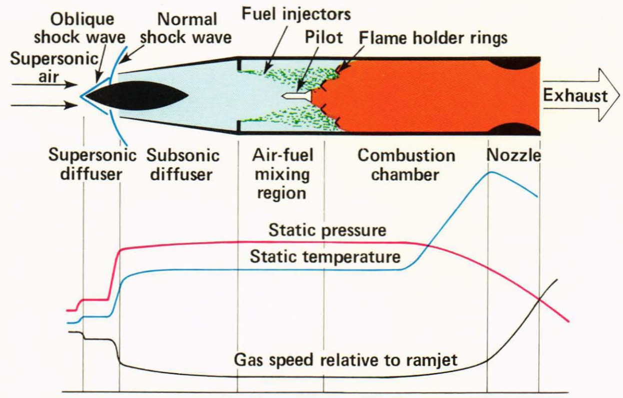


Figure 1 — The ramjet principle is based on increasing the momentum of air passing through the engine. Air enters through a multiple-shock inlet and is converted from supersonic flow at ambient static pressure to subsonic flow at high static pressure. Fuel is mixed with the air, ignited by a pilot flame, and burned in a combustion zone stabilized by flameholders. Energy added to the gases by combustion produces an increase in the momentum of the exhaust. The exhaust momentum and pressure are in equilibrium with internal pressures in the ramjet. Thrust is produced by the vector sum of the forces resulting from pressures on the internal parts of the ramjet.

EARLY HISTORY OF RAMJET DEVELOPMENT

At the start of the program, it was essential to provide laboratory facilities in which ramjets of various sizes could be tested under conditions simulating those expected in flight. Construction of a facility for testing 6-inch-diameter ramjets at the APL Forest Grove Station in Silver Spring, Md., began in February 1945. Plans were made for construction of a full-scale ramjet test facility and supersonic wind tunnel to be located adjacent to the Lone Star Steel Company at Daingerfield, Tex., where large-capacity, high-pressure air blowers were available. The Consolidated Vultee Aircraft Company (CVAC) accepted an associate contract to build and operate this facility, which was later named the Ordnance Aerophysics Laboratory (OAL). Construction of OAL began in June 1945 and was completed in November 1946; testing was initiated in August 1945.

To provide an early indication of the feasibility of ramjet propulsion, a flight test program was started at Island Beach, N.J., utilizing a cluster of high-velocity aircraft rockets (HVAR Model 38) to accelerate 6-inch-diameter ramjet test vehicles to supersonic speed. The first flight tests were conducted on February 16, 1945, to provide data on supersonic drag and to test telemetering performance. The first unambiguous demonstration of ramjet thrust at supersonic speed occurred on June 13, 1945, using carbon disulfide as fuel, less than six months after initiation of the Bumblebee project. The first test demonstrating thrust in excess of drag at supersonic speed occurred in October 1945, using heptane as fuel (Fig. 2). This test vehicle design was modified in early 1946 by in-

THE SUNDAY SUN

BALTIMORE, SUNDAY, JUNE 9, 1946

THE BUMBLEBEE—Here is a model of the Navy's new ram jet engine called "The Bumblebee," taking off from a launching platform (bottom photo). The model in flight (upper photo) is capable of supersonic speeds up to 1,500 miles per hour at high altitudes.

Navy Reveals Supersonic Engine Exceeding 1,400 Miles An Hour

Ram Jet Weighs Only 70 Pounds Has No Moving Parts And Develops 2,000 Horsepower

By WILLIAM J. PERKINSON
[*Sun Staff Correspondent*]

Washington, June 8—The Navy's newest supersonic engine—The Bumblebee—which has hurtled through the air at speeds greater than 1,400 miles per hour was disclosed to the public tonight.

Developing more than 2,000 horsepower, the engine contains no moving parts, and weighs but 70 pounds. Conventional engines capable of producing that much power now weigh more than 2,000 pounds.

The ram jet engine, also known as the "Flying Stovepipe," which has been successfully flown a number of times, is described by the Navy Department as "neither a rocket, missile nor airplane, but simply a vehicle to get through the air at the speed of sound."

Launching Device Secret

Since the ram jet operates inefficiently at low speeds, there must be some way used to bring it up to high speeds. This is done by the use of catapults or rockets. After launching, the engine moves under its own power. Details of the Navy's launching device are still covered by the secrecy of the classified list.

The 600 scientists who are connected with the Bumblebee project faced the same problems as other scientists and engineers trying to perfect an engine capable of driving a plane or missle at supersonic speeds.

The problem is this:

Up to speeds approaching that of sound (743 miles per hour at sea level) scientists do not have to worry about the compressibility of air.

Air behaves like a liquid, thus as in a canoe if you wish to go faster you have to paddle faster and use more energy. But in airplanes and guided missiles, this energy comes from a power plant. The more energy a power plant developed the heavier it had to be.

Builds Up To Barrier

At the speed of sound this compressibility of the air builds up rapidly until it becomes a barrier that is extremely hard to penetrate. More power is needed, and before the advent of the jet engines with their high output for low weight, the problem seemed insurmountable.

Once on the other side of the barrier, in the realm of supersonic speeds, the resistance of the air to passage through it again decreases.

Yet within six months after the problem of producing a supersonic engine was turned over to the Hopkins scientists, the laboratory had successfully flown its first ram jet engine.

Looks Like Stovepipe

"The ram jet looks very much like a stovepipe," Dr. Richard B. Roberts, director of Project Bumblebee disclosed, with openings at both ends.

"It will not operate at speeds below 300 to 500 miles per hour, so we developed a special launching device to get the engine to that speed," he added.

As the engine hurtles through the air, air is scooped into a cone-shaped narrow front opening and compressed by the speed of the jet. This forward portion of the pipe is known as the diffuser. Approximately one third of the length of the pipe is used for diffusing the air, which is mixed with fuel from two injectors.

Wall Of Flame

To the rear of the diffuser is a combustion chamber where a wall of flame increases the momentum of the air as it expands in the diffuser.

This flame front also produces a back pressure which is exerted on the walls of the conical shaped diffuser. The forward thrust of the air on the diffuser's inner walls is what makes the jet engine go. The reaction to this forward thrust is flaming exhaust gases, whose temperatures are above 1,000 degrees Fahrenheit.

Even after it was determined in just what proportion the flame front, fuel inlets and diffusers were to be spaced, other problems arose.

There was the need to record data obtained by actual experiments, and the need to obtain a testing ground.

Must Be Tested In Motion

The ram jets cannot be tested statically, that is on the ground. They must be moved through the air, either in free flight or in a wind tunnel.

But there wasn't time to construct the supersonic wind tunnels necessary. It was decided to test the missiles in flight off Island Beach, N.

At the time the tests were started there was only one supersonic wind tunnel in the country; that was located at Aberdeen Proving Ground. (The Germans are reported to have had 30 such supersonic tunnels.)

The ram jet was first launched "cold"; that is, without the use of its fuel. This was necessary so that scientists could determine the flight characteristics of the engine's carrier. Later the engine was fired, using its own power.

Small Instruments Needed

Since the ram-jet engines being tested were extremely small, it was necessary to develop new means of telemetering information back to the ground. Telemetering is a method by which such data as pressure, temperatures, fuel flows and altitude can be broadcast back to field equipment at the test site.

It was necessary to develop equipment so small and compact that a four-channel radio system, complete with power supplies, measuring instruments and broadcasting equipment, could be contained in a space only slightly larger than a man's two hands.

Here the laboratories' prior work on the proximity fuse, and its close connections with other universities and industrialists paid off.

"Without the components developed for the proximity fuse, the job of relaying the data back to the ground for analysis could not be done," Dr. Roberts said.

Figure 2 — *The Sunday Sun* of Baltimore, reported on June 9, 1946, the development of a supersonic ramjet engine. Photo courtesy of World Wide Photos.

creasing the diameter of the forward section to 8.5 inches in order to provide additional packaging space for fuel, fuel metering equipment, instrumentation, and telemetering, as well as to increase the drag to make the unit less likely to accelerate to destruction when operated with fuel-rich fuel-air mixtures. This unit, Model 3B, was named Cobra because of the enlarged front end (Fig. 3).

In late 1945, representatives of Curtiss-Wright, CVAC, and APL met to plan an 18-inch-diameter prototype missile called the Ramjet Test Vehicle (RTV). This RTV was built by the Cornell Aeronautical Laboratory and was first tested at OAL in December 1945. It was designed to carry guidance equipment and a warhead but was unable to withstand the structural stresses of a ground test in a free jet. The only flight test of an RTV used kerosene fuel and produced a maximum acceleration of 2.5 g and a maximum velocity of 2200 feet per second. Further tests of 18-inch-diameter engines were conducted using a similar unit, called the Burner Test Vehicle (BTV), in which the guidance and warhead weight allowance was relocated in a stronger structure.

With the demise of the RTV as a prototype, a larger unit, called the Experimental Prototype Missile (XPM), was designed in late 1946, with a body diameter of 28 inches and a combustion chamber diameter of 24 inches (Fig. 4). The first XPM propulsion test vehicle was flown in March 1949 at the Naval Ordnance Test Station, China Lake, Calif. The predicted thrust was produced, but the engine was extinguished after 7 seconds of operation because improper fuel control caused an excessively fuel-rich mixture. Later flight tests were successful.

The ramjet engine designs, from the 6-inch Model 3B up to the 24-inch XPM, were all basically similar. They had "normal-shock" air inlets that were simple in design and not prone to producing pressure oscillations when the heat release of the combustion chamber or the presence of a tandem booster prevented maximum capture of the inlet air stream. The fuel injectors were simple tubes. The flameholders were combinations of blunt baffles to provide sheltered burning zones and interconnecting "gutters" to spread flame from the more sheltered piloting zones to the main fuel-air stream (Fig. 5). Fuel control progressed from constant fuel flow devices to more sophisticated ones, culminating in the XPM fuel control that throttled the fuel flow within the allowable combustion limits to provide constant-Mach-number flight.

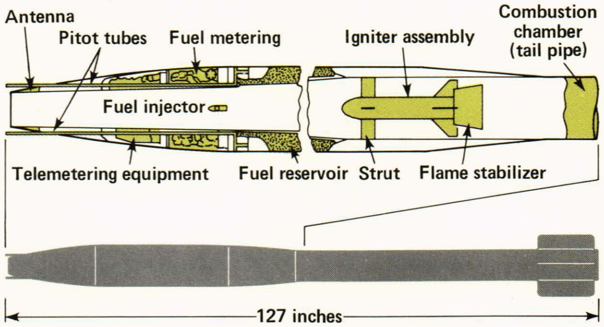


Figure 3 — Cobra ramjet (Model 3B) was the first of a series of test vehicles. Ram pressure was employed to force the fuel out of a flexible neoprene bag into the air duct near the diffuser intake where static pressure was low. The fuel rate was determined by the pressure differential that occurred across a fixed orifice. Ignition of the fuel mixture was by a pyrotechnic flare that burned throughout flight. The tailpipe was made from a stainless steel exhaust pipe from a fighter aircraft. Although the Cobra weighed only 70 pounds, it developed between 2000 and 3000 horsepower — as much as a big bomber engine.

THE TALOS COMBUSTION CHAMBER

High-Altitude Performance

The major problem with early Bumblebee ramjet engines was their inability to provide stable, efficient combustion for long periods at an altitude of 60,000 feet and an airspeed of 2000 feet per second. At these conditions, the combustion chamber had to operate at a pressure of one third atmosphere and at an inlet air temperature of 200°F. To meet this goal, CVAC had initiated tests of a "can"-type flameholder, based on turbojet technology. This development led to a completely different type of flameholding system (Fig. 6) that offered a solution for satisfactory operation at high altitude. Low- and high-altitude tests were conducted on this design in the summer of 1950. The development was successful, and all Talos combustion chambers used this general configuration. The design was unique in its ability to burn efficiently at low air temperatures and pressures. Combustion efficiencies (the ratio of theoretical to actual fuel flow for a given heat release) met or exceeded the ini-

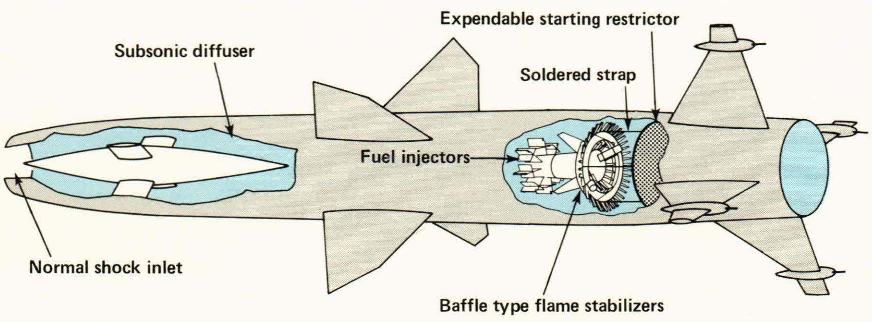
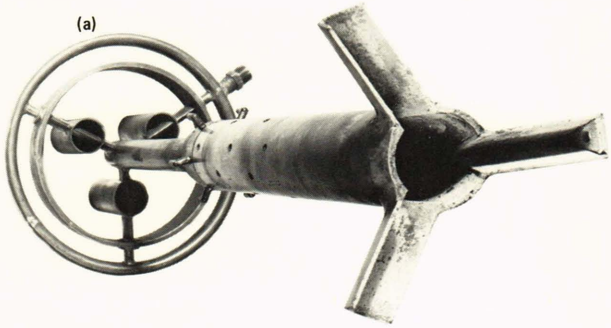


Figure 4 — The XPM ramjet engine required a starting restrictor to permit ignition. This starting restrictor was attached within the combustion chamber with soldered straps to block the duct partially and reduce the flow velocity. On ignition, the solder melted gradually and the restrictor was blown out of the exit.

(a)



(b)

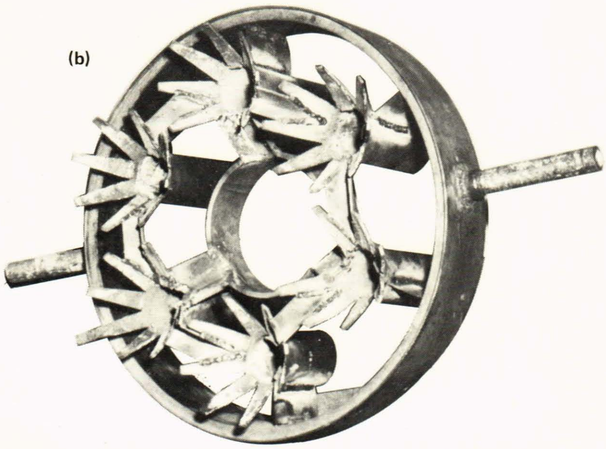


Figure 5 — Flameholder hardware for ramjets in 1946 were combinations of blunt baffles to provide sheltered burning zones and interconnecting gutters to spread flame from sheltered piloting zones to the main fuel-air stream. View (a) shows the fuel injector and radial gutter developed for a 6-inch ramjet. View (b) shows a piloted rake for an 18-inch combustor. The central ring fits into a pilot cone and connects the pilot to the rakes by radial gutters.

tially desired values. This combustion chamber design was frozen on June 1, 1951.

Combustion Chamber and Tailpipe Durability

An ensuing development problem of this combustion chamber design was to improve durability — the ability to maintain the integrity of the sheet metal "can" structure needed for flame stabilization. This problem is placed in perspective when one considers that stoichiometric burning will produce gases at about 3500°F and the melting point of stainless steel is no higher than 2800°F. The solution consisted of providing carefully controlled coatings of zirconia on all surfaces exposed to hot gases to prevent oxidation and to interpose cooling air between the hot combustion products and the metal structures. Persistent burnthrough was located at the intersection of the pilot can and the cooling shroud, where fuel tended to collect in the dead zone. The solution was to operate the pilot as fuel-rich as possible to provide enough fuel in the dead zone for fuel cooling in a local atmosphere too rich to burn. Another durability problem was caused by flow wakes behind fuel system components, which resulted in local reduction of airflow into the cooling shroud and hence degradation of wall cooling. This problem was solved by the installation of small airfoil sections, termed turbulators, to reenergize the boundary layer and the wake. The last of the durability problems was revealed by the first two low-angle shipboard firings of the higher speed Unified Talos (SAM-N-6c1). Both missiles failed because of burnthrough of the combustion chamber wall. The solution was found in increasing metal and zirconia thicknesses, but with a penalty of added weight.

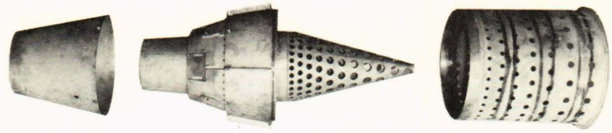


Figure 6 — The can-type flameholder operated with good efficiency at both high and low altitudes. A fuel-air mixture flows through holes in the can wall, and recirculation zones are established behind the holes to act as flame-stabilizing elements.

Combustion Efficiency

A major improvement in combustion efficiency was made for the higher speed and longer range missiles. The higher speed made it possible to reduce the exit nozzle throat diameter and thereby reduce the air velocity within the engine. Six inches were added to the combustion chamber length to improve combustion efficiency for high-altitude cruise. Combustor pressure losses were reduced somewhat by minor redistribution of airflow within the combustion chamber and careful attention to the angle and concentricity of the flow dividers at the combustion chamber entrance.

THE INLET

The function of a ramjet air inlet is to capture the desired airflow and reduce the air velocity from supersonic speeds to values acceptable to the combustion system with the highest practical pressure recovery. Fundamental studies by Oswatitsch in Germany and Kantrowitz and Donaldson in the United States demonstrated both analytically and experimentally what variations of pressure recovery could be expected in supersonic flow, as a function of Mach number, for single shock and multiple external conical shock air inlets. This established the fundamental design requirements for subsequent supersonic diffuser development.

For external multiple shock inlets, the compression is a three-stage process. In the first stage, the airspeed is decelerated to a reduced Mach number in passing through one or more conical shock waves. The second stage is the compression through a normal shock wave near the intake lip to produce subsonic flow. The third stage is the subsonic diffusion of air to produce high pressure at the combustion chamber.

All Talos engines were designed to operate subcritically, that is, at less than maximum air capture (Fig. 7) when the pressure within the combustion chamber

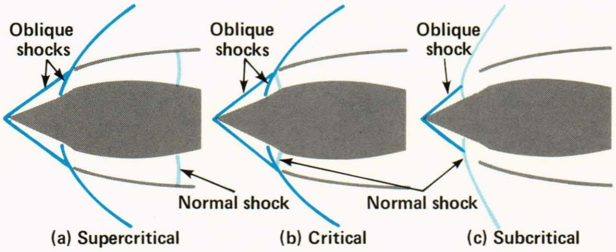


Figure 7 — Modes of diffuser operation are supercritical, critical, and subcritical. (a) Supercritical operation results when the normal shock is downstream from the cowl lip. It occurs at lean fuel/air mixtures. (b) Critical operation occurs when the normal shock is near the cowl lip. This takes place at an intermediate fuel/air mixture and is the most efficient operating point. (c) Subcritical operation results when the normal shock is ahead of the cowl lip. This occurs at rich fuel/air mixtures.

was high, providing maximum engine thrust. Operation in the subcritical regime tends toward instability of the overall diffuser-combustor system, permitting pressure oscillations that cause reduced thrust, missile structure vibration, and extinction of the combustion when operating near the combustion stability limit. Much of the inlet development effort was devoted to establishing the limits of acceptable subcritical operation by wind tunnel tests and overall engine free-jet tests.

Three air inlet designs were implemented before the Unified Talos configuration was established. The initial air inlet for the prototype Talos was a single-cone design, based on National Advisory Committee for Aeronautics (NACA) data that produced significantly better pressure recovery than did a normal shock inlet. During 1953, the entire ramjet system was redesigned for the first tactical missile. The cone angle of the inlet was increased to provide higher supersonic compression. These changes permitted an increase in inlet capture area from 205 to 235 square inches and a decrease in exit nozzle throat size from 70 to 65% of the body area, resulting in an increase in thrust capability. The "W" versions (nuclear warhead capability) of Talos had identical inlet cone shapes forward of the cowl lip but a slightly reduced capture area to compensate for the additional internal pressure loss in the annulus surrounding the larger inner body. In the latter part of 1953, another inlet redesign was needed to accommodate higher operating Mach numbers. A double-cone external compression surface was selected, with a forward cone half-angle of 25° and a second half-angle of 35°. This higher compression angle, combined with higher flight Mach numbers, resulted in a maximum inlet capture area of 360 square inches. The exit nozzle throat size was kept at 65% of the body area.

FUEL SELECTION CRITERIA

Selection of a suitable fuel for a prescribed flight envelope of missile speed and altitude for the ramjet engine depends on optimizing three criteria: (a) the fuel should have favorable thermochemical performance characteristics, expressible in terms of fuel specific impulse; (b) its rates of reaction with air should be such that an uncomplicated combustion chamber can be designed that will provide high combustion efficiency; and (c) fuel handling characteristics and costs should be within reasonable bounds. What weight is to be placed on each criterion depends on the specific engine performance to be achieved. For example, flight range is a very sensitive function of combustion efficiency and favorable thermochemical characteristics of the fuel. If long flight range is desired, criteria (a) and (b) need to be maximized.

The Talos system was designed to begin self-sustained operation at the termination of the solid rocket boost phase and to accelerate to Mach 2.5 during climb to cruise altitude. Long range was to be achieved by flying at altitudes of approximately 60,000 feet. These flight conditions of speed and altitude fixed the temperature/pressure regime for the combustion chamber in which fuel was to be injected, ignited, and burned. The thrust-producing temperature changes in the working fluid were achieved by varying the concentration of fuel in the air streams. At the start of the Talos development program, fuels were selected in which the reaction rate criterion (b) was emphasized at the expense of high thermochemical performance. Proof of principle was achieved with carbon disulfide and propylene oxide, both substantially more reactive than fuels based on carbon and hydrogen (hydrocarbons) alone.

As experience with the design of effective fuel injectors and flame stabilization devices grew, it became possible to turn to hydrocarbon-based fuels that would satisfy criteria (a) and (b) and also meet the operational requirements of reasonable cost and safe handling. By and large, hydrocarbon fuels rank high in all three of the fuel-selection criteria and have, therefore, been used as the preferred fuels. Only boron hydrides (in which boron acts as the hydrogen "carrier") offer substantial improvements in both criteria (a) and (b), with some reduction in criterion (c).

Table 1 summarizes the suitability of fuels that were investigated in the course of the Talos development. Some sulfur- and oxygen-containing fuels offer benefits of ease of ignition and rapid flame propagation but at the expense of thrust per unit weight of fuel. Boron hydrides provide superior kinetic performance and high fuel specific impulses but at the expense of cost and ease of handling. Saturated aliphatic or aromatic hydrocarbons, while somewhat deficient in reactivity, nevertheless perform well when extreme flight ranges are not of vital importance.

As military specifications were developed for jet engine fuels, JP-5 was selected for use in the early production Talos. The value of higher density fuels in providing additional range capability was recognized early in the engine development program, and tests with tetralin were conducted at OAL. A less expensive high-density fuel was methylcyclopentadiene

Table 1 — Suitability of fuels in Talos ramjet engines.

	S_a	S_f	$S_{f,d}$	*Kinetics*	*Toxicity*	*Storage*	*Thermal Stability*	*Viscosity*	*Cost*
Carbon disulfide	P	P	P	E	F	G	G	G	G
Kerosene	G	G	F	F	E	E	E	G	E
Propylene oxide	F	F	F	G	G	F	F	G	F
Methylcyclopentadiene dimer	G	G	G	F	G	F	F	G	F
Kerosene-boron slurries	G	E	G	F	E	F	E	P	F
Methylacetylene	E	G	F	E	G	F	F	G	F
Boron hydrides	E	E	E	E	P	F	P	G	P

P = Poor
F = Fair
G = Good
E = Excellent

S_a = air specific impulse (stream thrust at sonic velocity divided by air mass flow)
S_f = fuel specific impulse (S_a/(fuel/air ratio))
$S_{f,d}$ = density specific impulse ($S_f \times$ density)

dimer, which has 12% higher volumetric heat release than JP-5. The dimer fuel was successfully tested in the first tactical combustor at OAL in 1955. In 1964, when additional range was desired for the Unified Talos, the use of that fuel was reconsidered. However, its storage stability characteristics were unsatisfactory because, as an unsaturated hydrocarbon, it tended to polymerize with time. A program was completed to hydrogenate the dimer to form a stable saturated compound. This fuel was used after 1966.

THE FUEL SYSTEM

The Talos fuel system provided fuel to the combustion chamber to maintain stable combustion and to control engine thrust. For maximum stability of operation, the pilot required fuel at a rate that provided an approximately constant and optimum fuel-to-air ratio. For the main combustor, the fuel rate was varied from zero to a maximum near the overall stoichiometric fuel-to-air ratio to provide the required thrust. Fuel systems for the prototype and First Tactical Talos controlled the fuel flow to maintain constant speed. Since the temperature-sensing units used to control velocity were prone to malfunction, the fuel systems for Extended Range Talos and Unified Talos were designed to control Mach number as a function of altitude.

The fuel controls operated from sea level to 70,000 feet altitude, representing a 17:1 variation in airflow through the engine. They also had to provide fuel for engine ignition within a few tenths of seconds after missile separation from the rocket booster. Fuel had to be injected into the air stream to provide local air-to-fuel ratios that were within the burning limits of the fuel. Other considerations for fuel system design included: (a) high flight accelerations (about 15 g longitudinally during boost and up to about 15 g laterally in flight); (b) accelerations when missile roll-control was established; (c) low combustion chamber pressure at high altitude; (d) vibration and heating during flight; and (e) sudden variations in pressure and airflow at the time of rocket booster separation. Small volume and weight, compatibility with the annular packaging space of the missile, long storage life, reliability, and low cost were additional design considerations.

Figure 8 shows the main elements of the Talos fuel system. The outlet of the annular fuel tank was sealed by a valve controlled by nitrogen pressure. Stored under pressure, nitrogen was released by a valve that was opened by acceleration during boost, pressurizing the fuel bladders inside the fuel tank and opening the fuel tank valve. Fuel flow from the tank was maintained during periods of high missile acceleration by channels within the tank formed of perforated sheet-metal segments. The bladder material had to withstand the stresses generated by fuel motion and the heating by the hot walls of the central air duct.

A centrifugal pump driven by an air turbine was the chief means of moving the fuel to the fuel nozzles. High-pressure air bled from the central air duct provided a suitable energy source for the air turbine. Fuel pump inlet pressure was provided by the nitrogen pressurization.

Separate regulators were used for the pilot and main fuel. A probe ahead of the engine inlet provided freestream pitot and static pressure measurements for the fuel system. These pressures were used to measure flight Mach number, altitude, and engine airflow. The fuel regulators were required to control fuel flow rates over a range of about 20:1 for the pilot burner and more than 100:1 for the main burner.

Main and pilot fuel entered the combustion chamber in concentric pipes. In either case, the fuel was

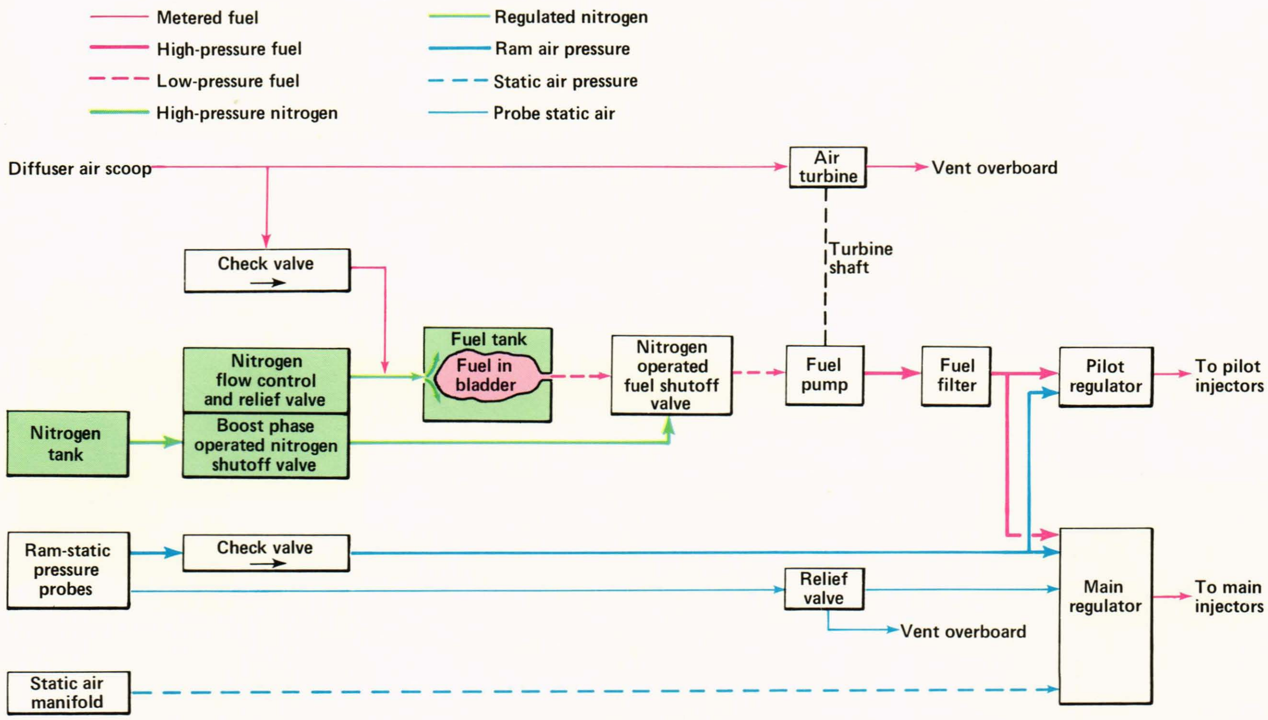


Figure 8 — The Talos ramjet fuel system maintained stable combustion and controlled engine thrust. The fuel tank was normally pressurized with nitrogen, but diffuser pressure was also available as backup. A centrifugal pump driven by an air turbine provided high-pressure fuel to the pilot and main fuel regulators. Ram and static air pressures were used to regulate the fuel flow. The regulator compartment was vented to the atmosphere through louvers and was employed as an atmospheric sump for the regulator.

discharged into the air stream through an annular array of nozzles. The injector system maintained proper fuel distribution during high-g lateral maneuvers and sustained proper fuel flow in the presence of variations in air pressure. Nozzles used in the pilot injector had linear pressure-versus-fuel flow characteristics that assured uniform flow distribution to the pilot. The main fuel injectors used spring-loaded, fixed-pressure nozzles and a fuel distribution valve to maintain uniform fuel distribution to the individual nozzles.

THE UNIFIED TALOS RAMJET PROPULSION SYSTEM

No major changes were made to the ramjet design after the Unified Talos configuration was established. This final design provided reliable and adequate propulsion for all flight conditions that fell within the Talos operating envelope.

The supersonic inlet employed double-cone external compression and was designed for best operation for flight Mach numbers ranging from 2.0 to 2.5. The engine operated subcritically at low Mach number but inlet stability was maintained at maximum engine thrust.

The fuel rate was controlled so that the flight Mach number was regulated between 2.0 and 2.5 depending on the ambient static pressure (which is related to altitude). Dimer or JP-5 fuel could be used with minor adjustments to the fuel regulator. The capacity of the fuel system provided a maximum range of 130 nautical miles with dimer and 115 nautical miles with JP-5.

The final Talos combustor is shown in Fig. 9. The combustor was constructed of conical sections and assembled to provide concentric regions where pilot flame and main air-fuel mixtures are combined to provide stable combustion. Holes in the central cone produced vortex wakes of relatively low speeds (less than the spreading speed of the flame), which provided the flameholding action (Fig. 10). Burnout of the combustor was prevented by proper distribution of the air and fuel and by appropriate zirconia coatings. Ramjet ignition was by a spark plug located in the pilot region. The length of the combustion chamber provided adequate time for efficient combustion. A contracting/expanding exit nozzle was employed to reduce air speed in the combustor and to match the combustor with the inlet.

A summary of Talos ramjet propulsion capabilities is given in Fig. 11. Two independent relations are shown: the maximum acceleration due to thrust, and deceleration due to drag. Horizontal flight and properties of the atmosphere for an NACA Standard Atmosphere are assumed. For a given altitude, the difference between the maximum acceleration from

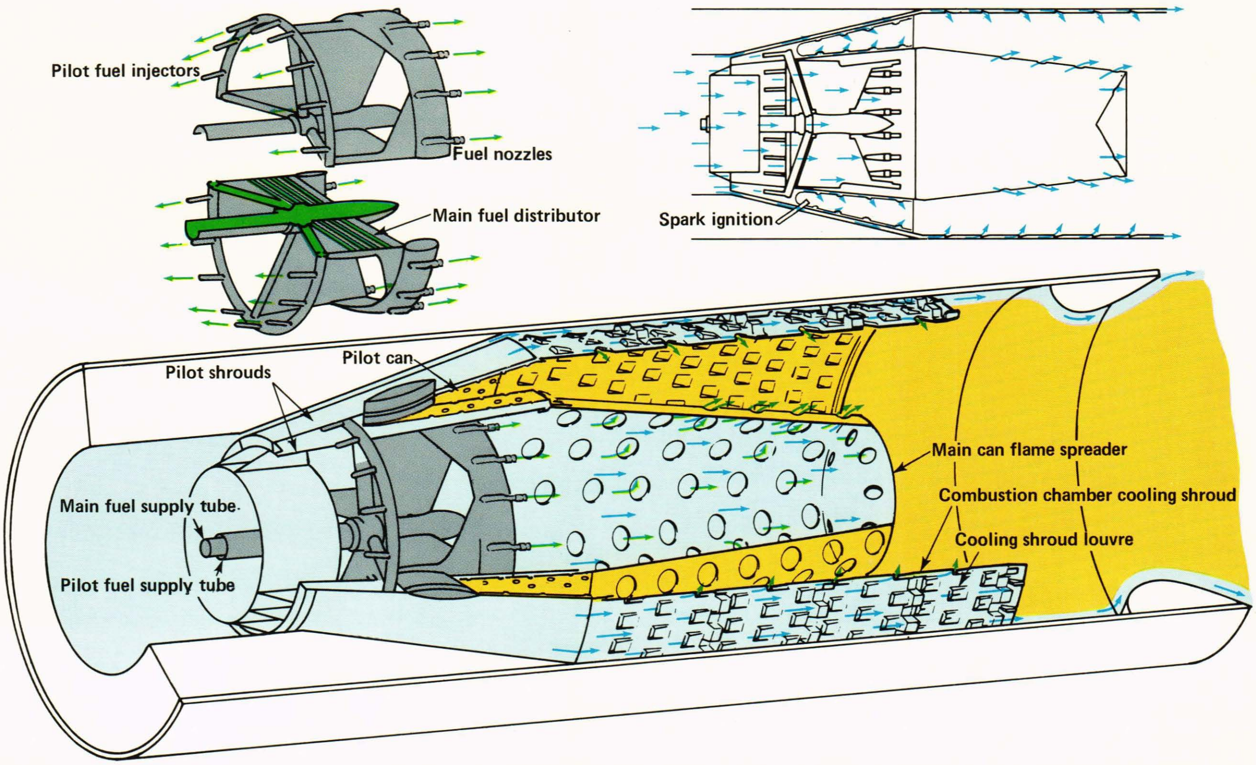


Figure 9 — The Talos combustion chamber design used approximately 20% of the captured inlet air along the outer wall for combustion chamber wall and nozzle cooling. Another 15% of the air passed into a pilot section, where pilot fuel was injected through high-pressure spray nozzles to maintain stable combustion under all conditions of flight. The remainder of the air flowed through the center of the engine to the main flamespreading section, where fuel was injected through low-pressure nozzles and burned to produce the engine thrust. Combustion chamber parts were ceramic-coated to prevent oxidation at high temperatures.

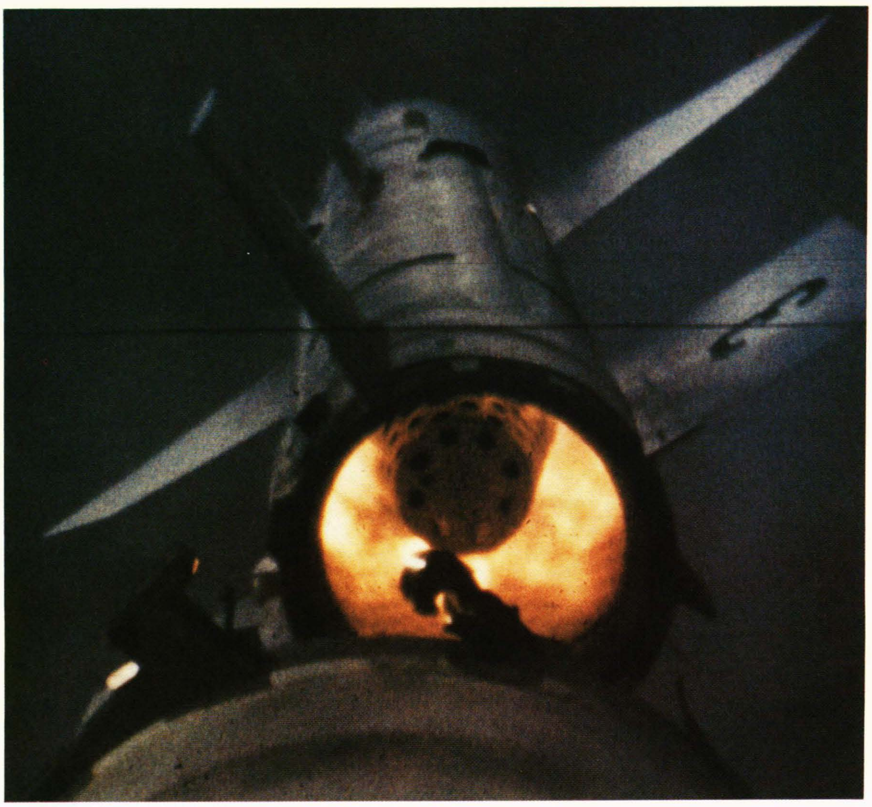


Figure 10 — Flameholding action in the Talos combustion chamber was accomplished by vortex wakes produced by jets from holes in the central cone. Flameholding action during a Talos flight test is shown as viewed from a booster rocket.

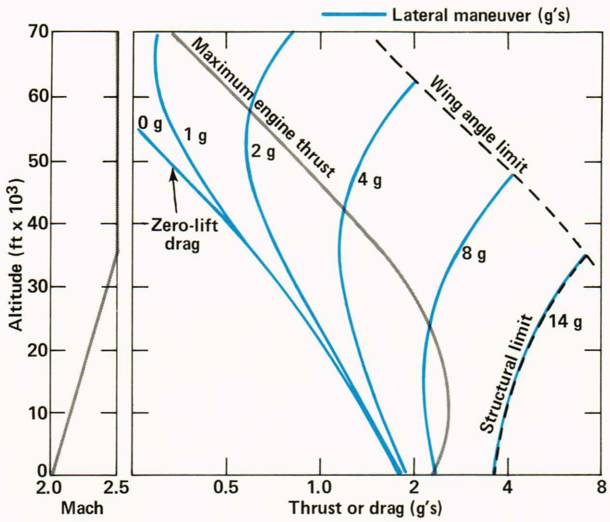


Figure 11 — Unified Talos ramjet engine performance is shown for the Mach number and altitude relation displayed at the left of the figure. Two independent relations are presented in the main figure: (a) maximum acceleration due to thrust, and (b) deceleration due to lateral maneuver. For a given altitude, the difference between relation (a) and relation (b) gives net available acceleration along the flight path. Operating points that occur to the right of the maximum engine thrust line will result in missile slowdown.

engine thrust and deceleration resulting from lateral maneuver gives the net available acceleration along the flight path. Operating points that occur to the right of the maximum engine thrust line will result in missile slowdown.

The characteristics shown in Fig. 11 have been demonstrated by comparison with over a hundred flight tests. The mean error in the thrust-minus-drag coefficient was less than 0.01, and the 1σ scatter about the mean was about 0.01. These errors are equivalent to errors in pressure of about 1% and represent better accuracy than can be found for individual points in ground testing.

RELIABILITY

Almost 1200 missiles using the Talos ramjet engine have been launched. During 25 years of testing, an overall system success rate of 96% was demonstrated. In the ongoing Vandal program that employs the Talos airframe and propulsion system as a supersonic target, an even better reliability of about 98% is being achieved, using propulsion systems that were built about 20 years ago.