NASA TECHNICAL MEMORANDUM

NASA TM X-67806

NASA TM X-67806

SHUTTLE AIRBREATHING PROPULSION

by Warner L. Stewart, Arthur J. Glassman, and Stanley M. Nosek
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at
Seventh Propulsion Joint Specialist Conference sponsored by the
American Institute of Aeronautics and Astronautics
Salt Lake City, Utah, June 14-18, 1971

SHUTTLE AIRBREATHING PROPULSION

Warner L. Stewart, Arthur J. Glassman, and Stanley M. Nosek
Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

Abstract

Airbreathing gas turbine engines to provide cruise, landing, go-around, and ferry capability for the shuttle vehicles face new requirements such as launch, space residence, and reentry. Also, hydrogen is being considered as an alternate fuel for the engines. It becomes necessary to determine which engines are most suitable and to examine them for modifications and technology required to meet the new requirements. This paper reviews the requirements imposed on the engine, the effect of fuel selection, and the design studies currently being conducted to assess candidate engine designs in light of the mission requirements.

Introduction

The NASA is currently engaged in definition and design studies, both inhouse and under contract, for a reusable two-stage space transportation system, known as the space shuttle. This system is intended to transport payloads into earth orbit and to return to earth at an overall cost greatly reduced from those of current systems. The shuttle vehicles must perform as launch vehicles, as spacecraft, and last, but not least, as aircraft.

A typical mission profile is shown in Fig. 1. After launch and staging, the first stage, or booster vehicle, reenters the atmosphere downrange and must cruise back to the launch site and make a horizontal landing. The second stage, or orbiter vehicle, proceeds to orbit. Upon deorbiting, the orbiter reenters the atmosphere, descends directly back to the launch site, and makes a horizontal landing. Both vehicles must have go-around capability; that is, they must be able to abort a landing attempt and circle the field to make another landing approach. In addition, both vehicles must have self-ferry capability, which means that they must be able to fly from one airfield to another like conventional aircraft. Airbreathing gas turbine engines will be used to provide propulsion for the various aircraft functions.

E-6263

The booster and orbiter mission requirements differ from each other to the extent that different engines could be optimum for each. Total thrust requirements (based on sea level static conditions) are about 200,000 lb for the booster and about 70,000 lb for the orbiter. The booster consumes a large amount of fuel during its more than 400 mile cruise back to the launch site, while the orbiter, which descends directly from space to the launch site, has no requirement for cruise during an operational mission. For minimizing development cost, however, there is a strong desire to use a common engine for both vehicles.

These engines, whether separate or common, must be exposed to launch, space, and reentry environments and then must be started in-flight after reentry. Although JP fuel is currently specified for the engines, the use of hydrogen, which has a very high energy content, is being studied as an attractive alternate fuel for the engines. The environmental conditions and the consideration of hydrogen fuel are new requirements for airbreathing gas turbine engines.

Thus, it becomes necessary to determine which engines are most suitable for the shuttle vehicles and to examine these engines with respect to the modifications and technology required to meet the new requirements. To do this, contracts were awarded to General Electric and Pratt & Whitney to study the use of both existing and new engines. This paper reviews the requirements imposed on the engine, the effect of fuel selection, and the contract design studies currently being conducted to assess the engine designs in light of the mission requirements.

Vehicle Configurations and Engine Installations

Both straight-wing and delta-wing vehicles have been studied by the shuttle vehicle contractors. The current designs of both McDonnell Douglas and North American Rockwell/General Dynamics feature delta wings for both vehicles with the boosters also having canards. The McDonnell Douglas booster shown in Fig. 2 has a tilted-end high wing with the airbreathing engines located in the canard. The engine compartment is closed during launch and reentry. For operation of the engines after reentry, doors open to form the engine inlet and a jet flap exhaust section.

The North American Rockwell/General Dynamics booster has low wings with the airbreathing engines, as indicated in Fig. 3, stowed in compartments in the wings and fuselage during launch and reentry. For operation after reentry, the podded engines are deployed as illustrated in Fig. 3. The rightmost engine shown in the inset is in the stowed position and the compartment doors are just beginning to open. The engines pivot through 180° to the fully deployed position represented by the leftmost engine.

The McDonnell Douglas orbiter is shown in Fig. 4. Stowed in compartments in the wings, the airbreathing engines are deployed downward after reentry. In the North American orbiter, the airbreathing engines are stowed in compartments in the upper part of the sides of the vehicle. As illustrated in Fig. 5, these engines are hinged and swing outward upon deployment, with the upper engines located axially forward of the lower engines. The configurations shown in Figs. 2 to 5 are not necessarily the final designs of the vehicle contractors.

Engine Requirements

The requirements to be met by the airbreathing engines in propelling the shuttle vehicles are listed in Table 1. Total sea-level-static thrust is about 180 to 220,000 lb for the booster and about 60 to 75,000 lb for the orbiter. This large difference in thrust requirement would make it desirable, from a standpoint of number of engines per vehicle, to have different size engines for each vehicle. With a common low-thrust engine, a large number of engines must be used for the booster. With a common high-thrust engine, the orbiter would have excessive installed thrust because of engine-out requirements. The booster cruise of more than 400 miles (1 1/2 to 2 hr) per mission as opposed to no cruise for the obriter mission results in significantly different engine life requirements for the two vehicles. On the basis of 100 missions, a 500 hr life has been specified for the booster engines. A separate engine for the orbiter alone would require perhaps only 50 hr of life for the design mission. This reduced life requirement could be used to obtain increased thrust from a given engine in a manner as discussed later in the Design Modifications section. A common engine, of course, would have to meet the higher life requirement of the booster.

The booster cruise requirement makes engine fuel consumption a more important consideration for the booster than for the orbiter. As a result of the desire to reduce booster fuel weight, NASA originally specified that hydrogen, because of its high energy content and on-board availability, be given primary consideration as the engine fuel. Concern over the development and operation of a hydrogen-fueled airbreathing engine caused a subsequent change in study ground rules so as to give primary consideration to JP fuel for the engine. However, the fuel weight reduction afforded by the use of hydrogen, as shown in the next section, is sufficiently attractive so that hydrogen is still being studied as a possible alternate fuel.

The desire for a lightweight (high thrust-to-weight ratio) engine is stronger for the orbiter, where 1 lb of engine weight trades for 1 lb of payload, than for the booster, where about 5 lb of engine weight trade for 1 lb of payload. Another important difference between the two vehicles is the space exposure requirement. The booster will be exposed to the space environment for only several minutes and its engines would probably require little, if any, in the way of special provisions. The space residence requirement of 7 to 30 days for the orbiter will require special consideration to prevent loss of fluids, overheating or undercooling of fluids, and possible outgassing of nonmetallic materials.

The vehicles must be able to recover from an aborted landing attempt and circle the field to make another landing approach. Some of the missions being studied involve removal of the airbreathing engines from the orbiter in order to increase payload. For these particular missions, the orbiter must give up its go-around capability. In order to be able to fly some missions with engines on and some with engines off, and also to have the ferry capability required of both vehicles, the orbiter must be built with provisions for relatively easy mounting and removal of the airbreathing engines.

The engines must start reliably in-flight after, in the case of the orbiter, prolonged exposure to space. Sufficient thrust must be provided so that all parts of the mission can be flown with one engine out. In order to meet the shuttle vehicle flight-test schedule, engines must be available for delivery in 1975.

Engine and Fuel Selection

Selection of engines for the shuttle vehicles depends on such considerations as engine thrust, size, fuel consumption, and availability. A major variable affecting the engine performance parameters is engine bypass ratio. In Fig. 6(a), typical values of specific fuel consumption for both hydrogen and JP fuels are plotted against bypass ratio. The high energy content of hydrogen results in a fuel consumption that is about one-third that of JP. For the booster with its long cruise requirement, it would be expected that a high bypass ratio is desirable in order to reduce fuel consumption.

Specific thrust and engine diameter (for an assumed thrust of 20,000 lb) are plotted against bypass ratio in Fig. 6(b). The lower specific thrust and, consequently, larger size of higher bypass-ratio engines result in large and heavy installations that tend to offset the fuel weight advantage. Parametric studies of engine, installation, and fuel weights conducted under NASA contract by General Electric and Pratt & Whitney indicated that moderate bypass ratios of about 2 to 4 would be optimum for a hydrogen-fueled booster engine. It would be expected that, because of the higher fuel consumption, somewhat higher bypass ratios would be optimum for a JP-fueled booster engine.

For the orbiter, where fuel consumption is of minor consequence, it would be expected that a high-specific-thrust small-diameter engine is desirable. Thus, a low-bypass-ratio, less than 1, engine is of interest and even dry and afterburning turbojets have been considered. An engine to be used commonly for both vehicles should have a low to moderate bypass ratio, perhaps 0.5 to 2, in order not to severely penalize either vehicle.

Engine thrust level is another important consideration in the selection process. A 40 to 60,000-lb-thrust engine would give a desirable 4 to 6 engine configuration for the booster. However, because of the engine out requirement, use of this size engine in the orbiter would result in an excessive amount of installed thrust and associated weight. An engine with 15 to 20,000 lb of thrust would satisfy the orbiter, but would result in a very large number of engines for the booster. The use of a common engine, which would minimize development cost, must result in compromising what is the most desirable bypass ratio and size for either one or both of the vehicles.

Example installed engine and fuel weights, for both JP and hydrogen, are shown in Fig. 7. For the booster, the weights are for an example case having a constant gross-weight orbiter. The 144,000 lb of JP fuel weight is more than three times the engine weight, thus strongly emphasizing the importance of engine fuel consumption. Even with hydrogen, the fuel weight of 45,000 lb is more than the engine weight. The engine weight is slightly smaller with hydrogen than with JP because the booster vehicle is lighter and fewer engines are required. The additional weight of engine plus fuel with JP as compared to hydrogen is more than 100,000 lb for this illustration. Estimates made by vehicle contractors of the effect of the fuel plus engine weight difference show an increase in booster gross lift-off weight in the range of about one-half to one million pounds.

For the orbiter, with its small fuel requirement, about 4000 lb with JP or 1500 lb with hydrogen, the engine weight predominates. The fuel weight is only about 1/4 the engine weight for JP and about 1/10 the engine weight for hydrogen. Thus, for the orbiter, but not for the booster, it would be possible to consider the use of a high thrust-to-weight ratio engine having high fuel consumption in order to trade some increase in fuel weight for a reduction in engine weight.

If fuel weight were the only consideration, selection of the fuel would be straightforward because of the considerable reduction in gross lift-off weight obtained with hydrogen. However, there are other considerations. A hydrogen fuel system with a 500 hr life cannot be considered as existing technology and would require development. Thus, a hydrogen fuel system for the shuttle engines would require more development cost, a longer development time, and would entail more of a development risk than a JP fuel system. On the other hand, the use of JP fuel would require more cost for the heavier vehicle, a larger number of airbreathing and rocket engines, and more rocket propellant. Flying the vehicles from factory or alternate landing site to the launch site becomes more of a problem with hydrogen because of refueling considerations. The limited cruise range of the vehicles would require numerous refueling stops for a long distance flight. These are some of the factors that must be weighed and considered.

Engine Design Studies

As part of the shuttle technology program being conducted by NASA, engine study contracts were awarded to General Electric and Pratt & Whitney in June 1970. These were for nine month studies of shuttle airbreathing engines using hydrogen, which was the specified fuel at that time. As a result of the subsequent change of vehicle study assumptions to give primary consideration to JP fuel, these contracts were extended to also cover JP-fueled engines.

Objective and Scope

The first objective of the studies was to verify the performance potential of candidate engines. Using vehicle designs and mission profiles supplied by the vehicle contractors, the engine contractors determined engine, installation, fuel, and fuel tank weights for selected engines. Selected for study were existing engines, engines currently under development, advanced derivatives of developmental engines, and parametrically optimized new engines for both the booster and the orbiter. The study results indicated that the engine plus fuel weight savings associated with the use of separate engines rather than a common engine are relatively small. Further, the weight savings associated with optimized new engines as compared to engines currently under development do not appear sufficient to justify a new engine development.

In order to identify required engine modifications and potential problem areas associated with the shuttle application, one engine of each contractor was selected for detailed design study. The engine selections were made on the basis of performance potential and projected availability. A nonaugmented version of the F401 engine, a low bypass ratio turbofan currently under development, was selected by NASA for the Pratt & Whitney study. A mock-up of the augmented engine is shown in Fig. 8. The spool piece at the engine inlet (on the left) is not a part of the engine but is merely for adaptation of the engine to a particular test installation. In the nonaugmented version for the shuttle, a simple convergent nozzle would replace the afterburner and variable exhaust nozzle (sections to the right of the rear mount). The approximate length of the shuttle version of the engine is indicated in Fig. 8.

The selected General Electric engine was a nonaugmented version of the F101 engine, a moderate bypass ratio turbofan currently under development. A sketch of this engine, with the afterburner and the variable exhaust nozzle replaced by a simple nozzle, is shown in Fig. 9. Both the F401 and F101 engines are being developed for military applications and engine performance information remains classified.

The selected engines were studied to define modifications associated with shuttle requirements. The new requirements include shortened operating life as compared to the military application, possible use of hydrogen as fuel, and exposure to launch, space, and reentry environments. In particular, the engine duty cycle, fuel system and controls, lubrication system, materials, structural integrity, and in-flight start requirements were examined in detail. As a result, potential problem areas could be identified.

Finally, engine development and associated qualification programs were identified in terms of both time and cost, and performance specifications were determined for the modified engines. The hydrogen-engine studies and most of the JP-engine studies will be finished by the time this paper is presented. However, at the time of writing, only the hydrogen-engine studies were completed.

Design Modifications for Selected Engines

The detailed design studies indicated the nature of modifications that could or had to be made to the engines or its mode of operation. This section will concern itself with modifications associated with three areas among the many requiring consideration. These are engine life, the hydrogen fuel system, and the lubrication system.

Engine life. - An engine for a commercial or military aircraft is designed for a life that is much higher than the 500 hour requirement for the shuttle. Since higher turbine inlet temperature yields increased thrust, studies were made to determine the increase in turbine inlet temperature that will still give sufficient life to meet the shuttle requirement. This type of trade is illustrated in Fig. 10, which shows the results of a study made by Pratt & Whitney for an engine designed for several thousands of hours of life, 580 hr of which are at the maximum turbine inlet temperature. Life is rapidly diminished with increasing maximum turbine inlet temperature. For an increase of 150° F in maximum temperature, life at that temperature is reduced to about 10 hr. Since the shuttle mission requires maximum turbine inlet temperature only for climb-out after a landing abort, a life allowance of 10 hr at maximum temperature is ample for the 500 hr engine life requirement. Different engines as well as changes in duty cycle for a particular engine will result in changes in the allowable increase in maximum temperature. For instance, an increase in cruise turbine inlet temperature for the example considered above would result in a decrease in life at maximum turbine inlet temperature.

Engine life can also be traded for increased rotative speeds for the turbomachinery or a combination of higher temperature and higher speed. Increased speed can provide higher thrust by increasing pressure ratio, both fan and overall, and flow. It is the particular design of an engine that dictates the best way to reduce life in order to increase thrust.

Hydrogen fuel system. - A hydrogen fuel system will be a radical departure from a conventional JP fuel system. Hydrogen fuel systems with a 500-hr life and a maximum- to minimum-flow ratio of 50 do not exist. The development of such a system undoubtedly will be the critical element in the development of a hydrogen-fueled airbreathing engine for the shuttle. The objective of the fuel system studies conducted under the engine contracts was a preliminary definition of the fuel system and its major components.

Screening studies of candidate fuel pumps and pump-drive systems were first conducted. Pump configurations studied included staged centrifugal, fixed displacement vane, variable displacement vane, gear, piston, and combinations of centrifugal and positive displacement. Drive systems studied included direct engine gearbox, engine gearbox with variable speed transmission, hydraulic motor, air turbine, and hydrogen turbine drives. In order to achieve the required flow-metering accuracy, the hydrogen must be in a single phase, and both liquid and gaseous phase metering were considered.

The hydrogen fuel system selected by Pratt & Whitney as best satisfying operating requirements while minimizing development risk is shown in Fig. 11. It features a two-stage centrifugal fuel pump with an axial inducer to meet low NPSP requirements. The pump is directly driven by a variable-speed full-admission single-stage impulse turbine using compressor discharge bleed air. Bleed air requirements are less than 1 percent under all flow conditions. To prevent pressure fluctuations from being felt by the pump, a variable-area cavitating venturi provides system isolation between the pump and the hydrogen vaporizer, which is a single pass tube-type heat exchanger located at the fan turbine exit.

An all-electronic control system is used to provide fuel flow scheduling called for by the sensed parameters indicated in Fig. 11. For low flow rates, such as those obtained during the start transient, the variable-area cavitating venturi provides fuel flow control as a function of the measured flow rate. Tank pressurization provides the low flow during start-up. For the higher flows, metering is accomplished by controlling the area of the butterfly valve, which regulates flow of bleed air to the turbine drive and, therefore, varies fuel pump speed.

The General Electric fuel system differs in several respects from the Pratt & Whitney system discussed above. Two pumps in parallel are used to provide the flow. They are a low-flow positive displacement pump driven hydraulically and a high-flow centrifugal pump driven by a bleed air turbine. The discharge pressure is maintained supercritical and relatively constant for all flow rates, as opposed to the controlled variation in pressure with pump speed in the P&W concept. The G.E. design uses no vaporizer. The hydrogen is maintained in a supercritical liquid state during pumping, metering, and distribution.

Lubrication system. - The space shuttle environment introduces several potential problems for the lubrication system. These include vaporization of the oil, cold welding of metal surfaces, freezing of the oil, brinnelling of the bearings, and cooling the oil.

Current engine technology employs a dry-sump lubrication system with the bulk of the oil stored in an external tank. A schematic of a shuttle engine lubrication system, as proposed by General Electric, is shown in Fig. 12. Oil is supplied to all bearings and gears by an engine-driven main oil pump and scavenged from the sumps and gearboxes by scavenge pumps. It is then deaerated, cooled, and returned to the tank. The space vacuum environment, particularly in the case of the orbiter, will cause evaporation of the oil and loss through the shaft seals and engine vent. Aside from loss of the oil supply, there could occur contamination of the lubrication system by the residue left by the vaporized oil and contamination of critical surfaces on the vehicle by deposition of the oil vapors.

The oil vaporization problem can be controlled by isolating the oil until the engine is readied for use. General Electric proposes, as seen in Fig. 12, to do this by using shutoff valves in all lines connected to the oil tank. At the end of each mission, most of the oil can be removed from the system and returned to the tank by closing an oil supply valve early in the engine shutdown cycle. Any appreciable quantity not scavenged back to the tank in this manner must be manually drained from the engine after shutdown. Pratt & Whitney proposes to isolate the oil by adding a second tank with a connecting tube to the present tank and a single shutoff valve between the tanks. After shutdown, all oil would be drained and the isolated tank refilled. To insure removal of residual oil, as required particularly for the orbiter, flushing of the system is required.

Brinnelling of the bearings during launch and cold welding during orbital stay are possibilities that must be considered. Brinnelling has been known to occur during engine shipment as a result of vibratory and impact loading with the rotor stationary. Since the time during launch when the engines will be exposed to high vibration levels is relatively short, this may be no problem, especially since the bearings are designed for considerably more life than required for the shuttle. In the weightless environment during orbit, the main shaft bearings will be fully unloaded and vibration levels will be relatively low. It is unlikely, therefore, that sufficient loading will occur to cause cold welding of bearing surfaces. Testing during the engine development program will be required to verify that neither brinnelling nor cold welding will be a problem.

During the orbital phase of the mission, the oil tank temperature could stabilize below -65° F, which is the minimum temperature at which the oil will flow and just somewhat above the freezing temperature. One way to prevent freezing is to insulate the tank and provide a heater as shown in Fig. 12. Another solution is to use a recirculation pump and heat exchanger to condition the oil during the stay in orbit.

The engines being studied were designed to use oil-to-fuel heat exchangers to cool the oil. With hydrogen as fuel, the oil could easily freeze in the exchanger unless the hydrogen flow is carefully controlled. General Electric proposes to use an oil-to-hydrogen heat exchanger and carefully meter the fuel flow to prevent freezing. To avoid concern about freezing the oil in the cooler, Pratt & Whitney proposes to provide all the necessary cooling by means of oil-to-air heat exchangers located in the bypass duct.

In-flight Start

The shuttle mission requires airstarts at 30 to 40,000 feet altitude and subsonic Mach numbers with an extremely high confidence level. Before being started, the engines will have been subjected to launch, orbital residence for up to 30 days in the case of the orbiter, and reentry. The in-flight starting of a shuttle engine, therefore, can be expected to present more of a problem than the restarting of an engine that has flamed-out during operation. Among the major areas being studied as part of the in-flight start investigation are acceleration of the engine from zero to idle speed and combustor lightoff.

Engine acceleration. - The windmilling and airstarting characteristics of an engine are highly dependent upon the efficiencies of all the major components at extremely low speed conditions. Windmilling characteristics of turbomachinery are difficult to predict because of extreme off-design operation of the components. Cascade testing has seldom been conducted at extreme variations in incidence angle. Methods of projecting the known characteristics of one engine to represent a different engine have not proven very satisfactory. The windmilling and airstarting characteristics, therefore, will have to be determined experimentally.

The range of starting Mach numbers is such that starter assist will probably be required to achieve satisfactory start times. The necessary starter sizing cannot be established without complete knowledge of the engine's windmilling characteristics. In order to provide a meaningful assessment of starter size versus starting time, analyses were conducted for selected reentry trajectories. Two reentry paths studied by General Electric are shown in Fig. 13, where altitude is plotted against Mach number. Path 1 is at low Mach numbers and represents an extreme or most severe condition for starting. Path 2 is more representative of those currently being proposed by the vehicle contractors.

For the two paths, starter size as a function of starting time for the General Electric engine is shown in Fig. 14. For a given starter size above 200 lb-ft, there is only a small difference in starting times between the two reentry paths. This shows that, for this particular case, the higher Mach numbers of Path 2 provide little additional acceleration for the engine. For Path 2, a windmill start without assist would require more than 200 sec. Required starter size increases with shorter starting time, with the increase becoming quite rapid at times below about 40 sec. Since starting times of about 30 sec are desired for the mission, starter assist must be used. Reducing the start altitude would reduce the starter size requirement. Various types of starter systems being studied include hydraulic motors, cartridge, air turbines, and hot gas turbines.

Combustor lightoff. - Altitude lightoff in the combustor is an important step in the in-flight start process. In order for lightoff to occur, the pressure in the burner must be above a certain minimum value. For JP fuel, this minimum pressure is about 3 1/2 to 5 psia, depending upon the particular combustor design. For hydrogen, with its greater reactivity, the minimum pressure is less. Since ambient pressure as well as windmilling performance depend on altitude, the burner pressure limitation gives rise to a maximum altitude at which an engine will start. For the engines and reentry paths being considered for the shuttle, the maximum starting altitude is about 35 to 40,000 ft for JP fuel and higher for hydrogen.

Not only must the burner pressure be above minimum in order to achieve lightoff, but the Severity Parameter, PT/V, which is frequently used to correlate stability limits, and the fuel/air ratio must conform to certain limitations. Ignition limits for JP fuel, as determined experimentally by General Electric, are shown in Fig. 15, where equivalence ratio (fraction of stoichiometric fuel/air ratio) is plotted against relative values of Severity Parameter. Also shown are estimated ignition limits for hydrogen, which are seen to be less severe than for JP. A point representing a typical shuttle engine ignition condition is shown on the figure. This point falls within the region of ignition and stable combustion. Combustor lightoff is, therefore, not expected to be a problem for the shuttle application.

Concluding Remarks

Airbreathing gas turbine engines to provide cruise, landing, go-around, and ferry capability for the space shuttle vehicles are faced with requirements that are new for such engines. These engines must be exposed to launch, space, and reentry environments and then must be started in-flight after reentry. In addition, hydrogen is being considered as an attractive alternate fuel for the engines. Thus, it was necessary to determine which engines are most suitable for the shuttle vehicles and to examine these engines with respect to the modifications and technology required to meet the new requirements. This paper reviewed the requirements imposed on the engine, the effect of fuel selection, and the design studies currently being conducted to assess the engine designs in light of the mission requirements.

On the basis of engine performance and vehicle mission studies, the engines selected as prime candidates for the shuttle were nonaugmented versions of the F401 engine, a low bypass ratio turbofan currently being developed by Pratt & Whitney, and the F101 engine, a moderate bypass ratio turbofan currently being developed by General Electric. Design studies of these engines indicated that their modification for the shuttle mission appears to be very feasible and within existing technology. Only if hydrogen were selected as the engine fuel would there be a requirement for significant new technology.

The authors wish to acknowledge that this paper is based on material generated and provided by the shuttle engine design study contractors, General Electric and Pratt & Whitney, and the Phase B vehicle study contractors, McDonnell Douglas and the team of North America Rockwell and General Dynamics.

TABLE 1 ENGINE REQUIREMENTS

	Booster	Orbiter
Total installed thrust (SLS), lb	180 to 220,000	60 to 75,000
Cruise range, n mi	400 to 450	0
Life, hr	500	50
Fuel	JP or H_2	JP or H_2
Weight sensitivity, engine/payload	5/1	1/1
Space exposure	Minutes	7 to 30 days
Go-around	✓	✓
Ferry	✓	✓
Inflight start	✓	✓
Engine out	✓	✓
Engine delivery for vehicle test	1975	1975

E-6263

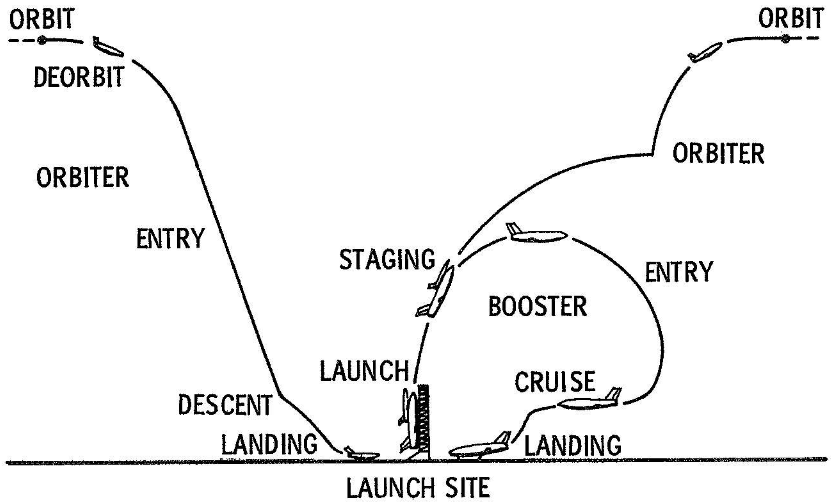


Figure 1. - Mission flight profile.

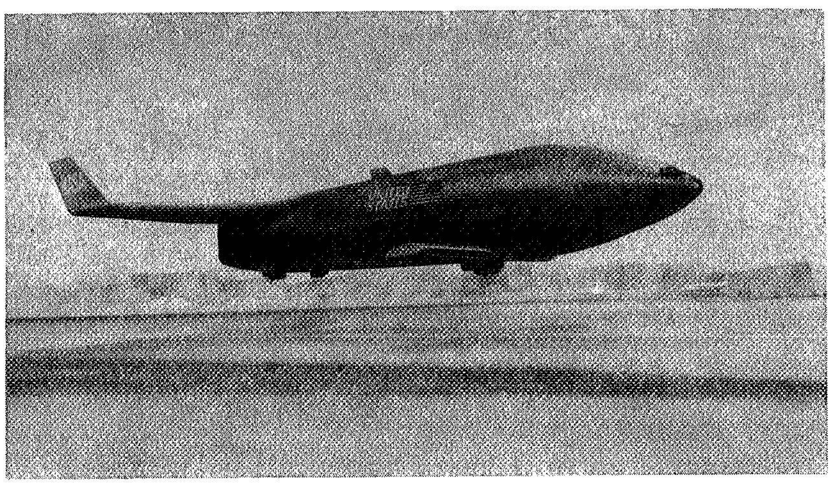


Figure 2. - Shuttle booster vehicle (McDonnell Douglas design).

E-6263

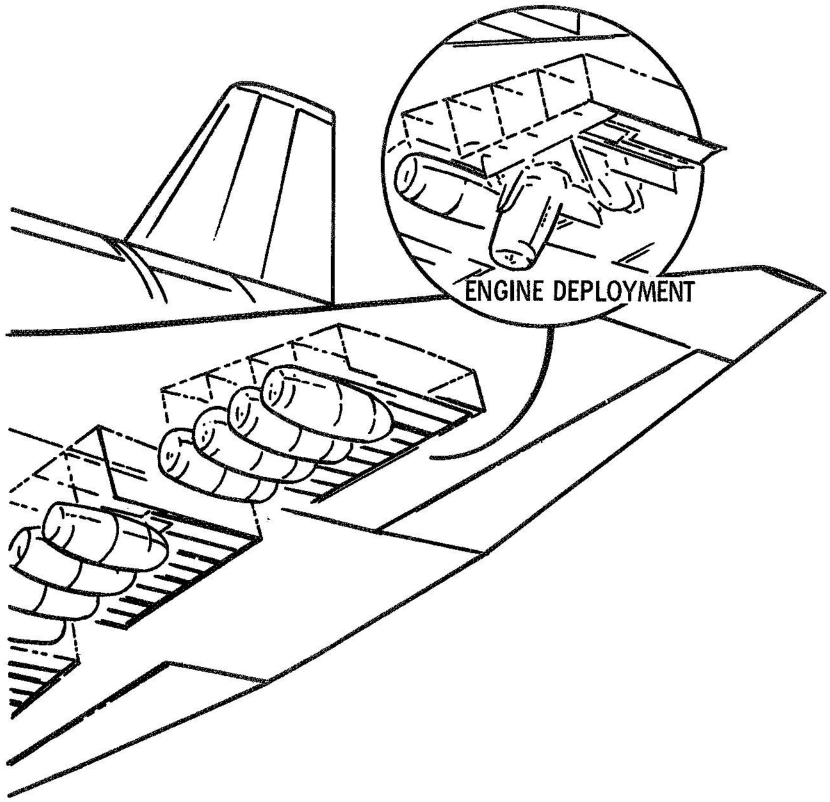


Figure 3. - Booster engine installation (North American / General Dynamics design).

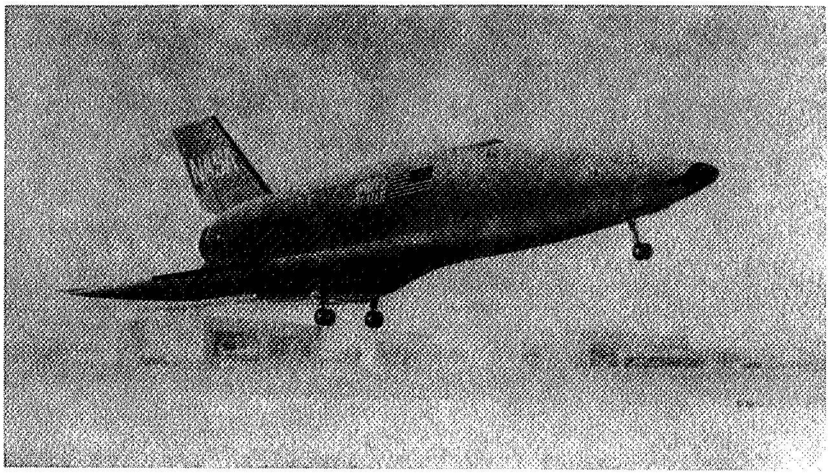


Figure 4. - Shuttle orbiter vehicle (McDonnell Douglas design).

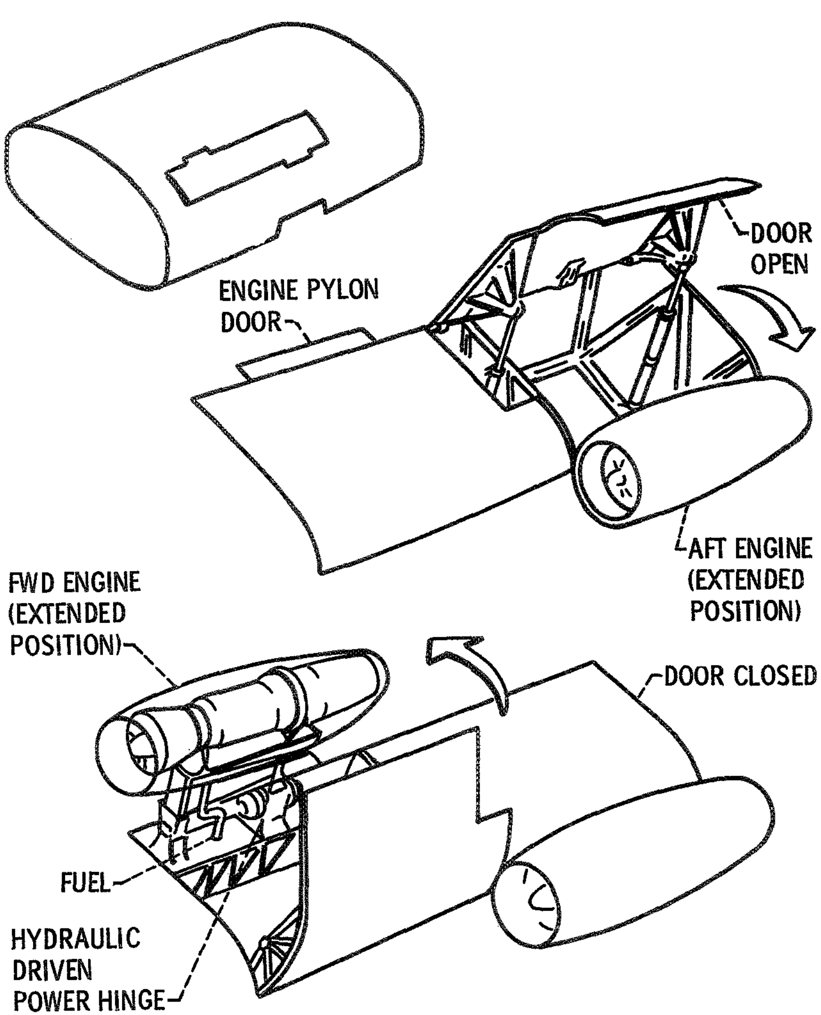
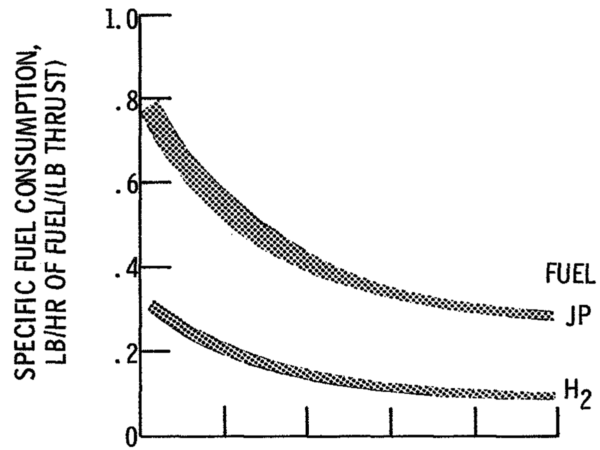
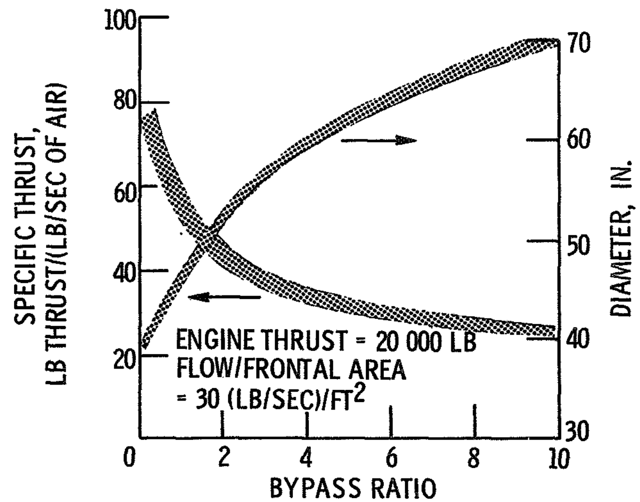


Figure 5. - Orbiter engine installation (North American design).



(A) SPECIFIC FUEL CONSUMPTION.



(B) SPECIFIC THRUST AND DIAMETER.

Figure 6. - Effect of bypass ratio on engine performance.

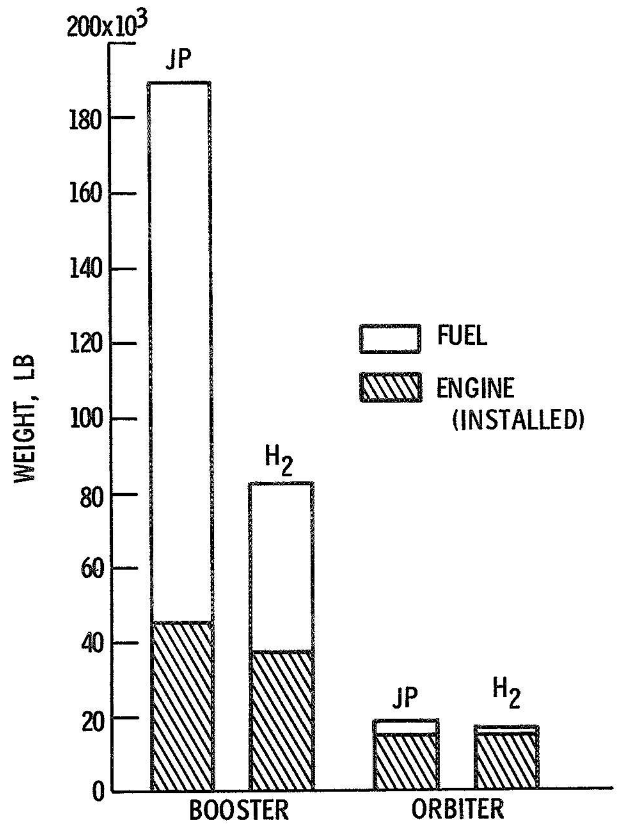


Figure 7. - Effect of fuel selection on engine and fuel weights.

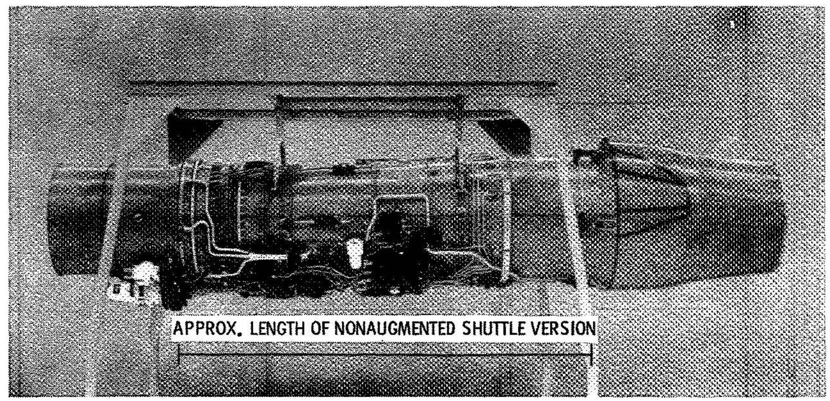


Figure 8. - Pratt & Whitney F401 engine mock-up.

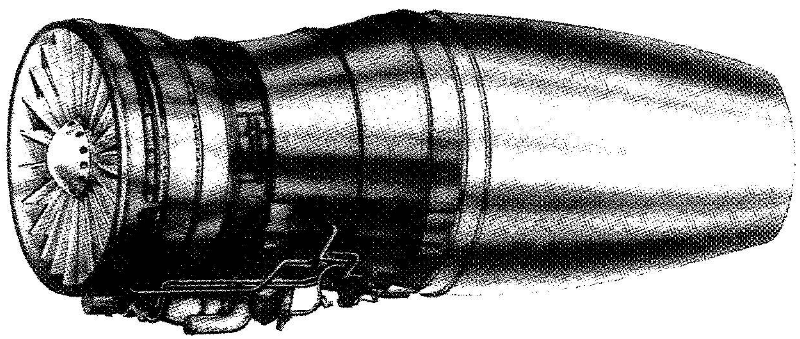


Figure 9. - Shuttle version sketch of General Electric F101 engine.

F-6263

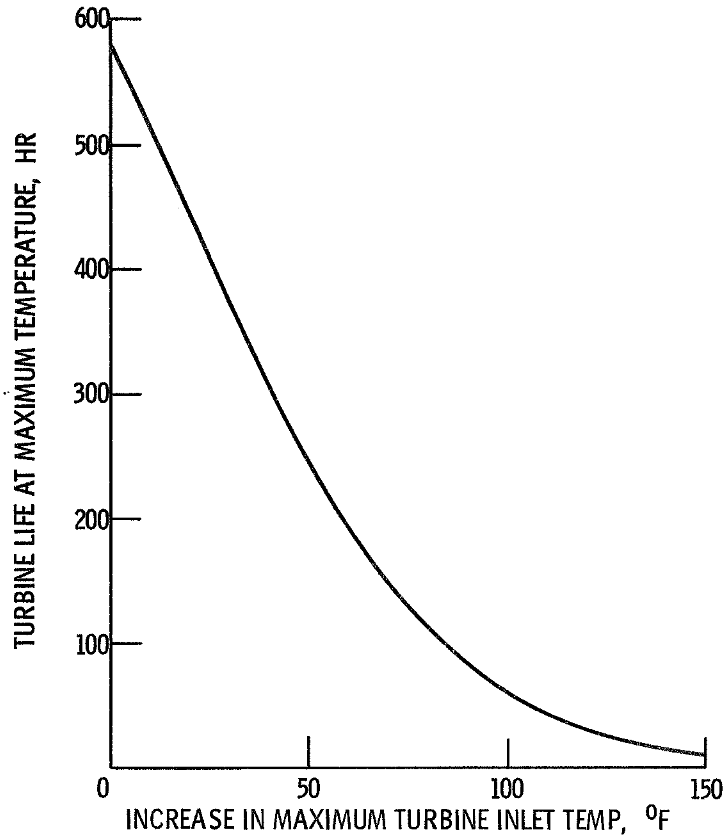


Figure 10. - Effect of turbine inlet temperature on turbine life (Pratt & Whitney engine).

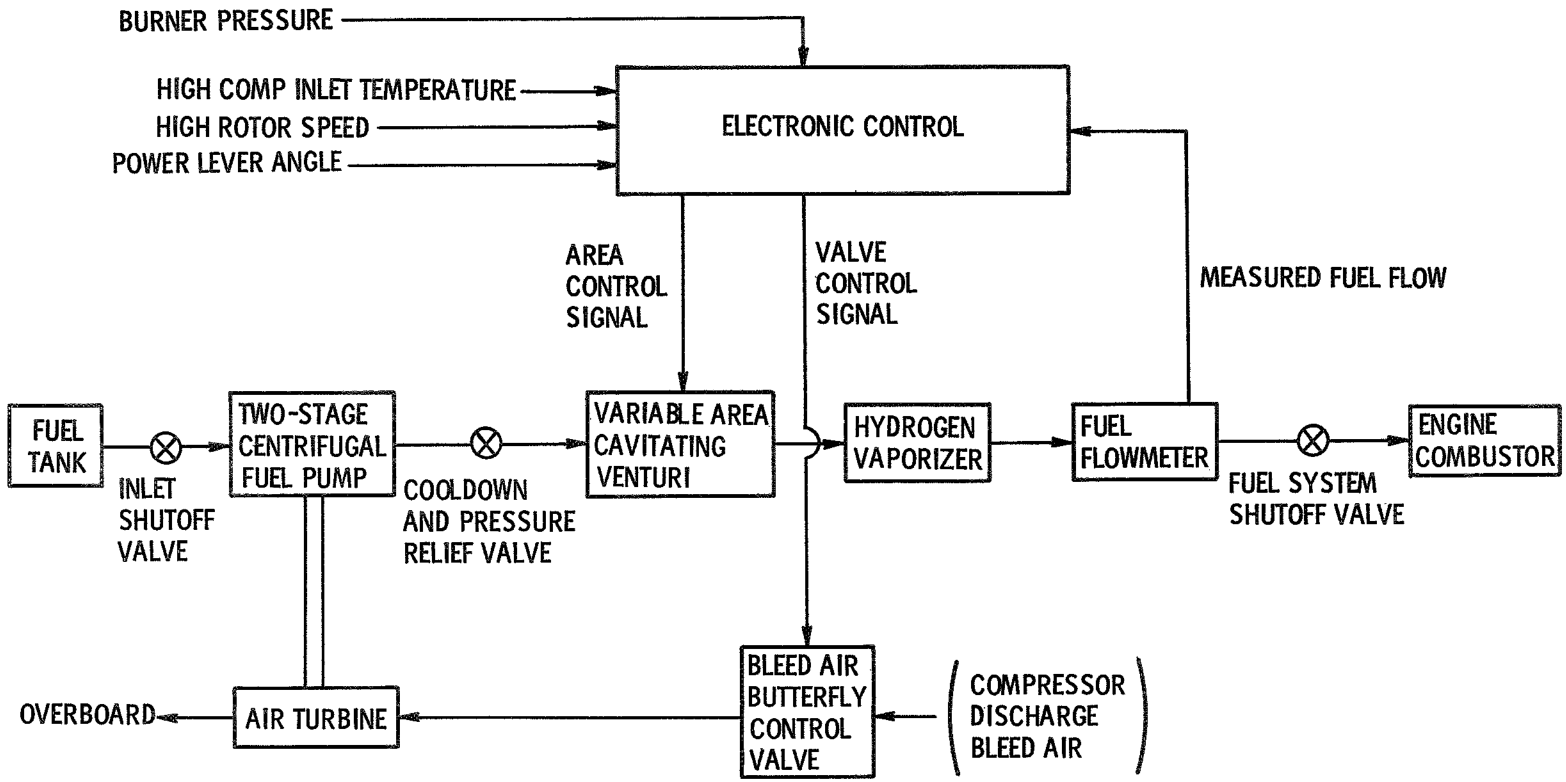


Figure 11. - Hydrogen fuel system schematic (Pratt & Whitney engine).

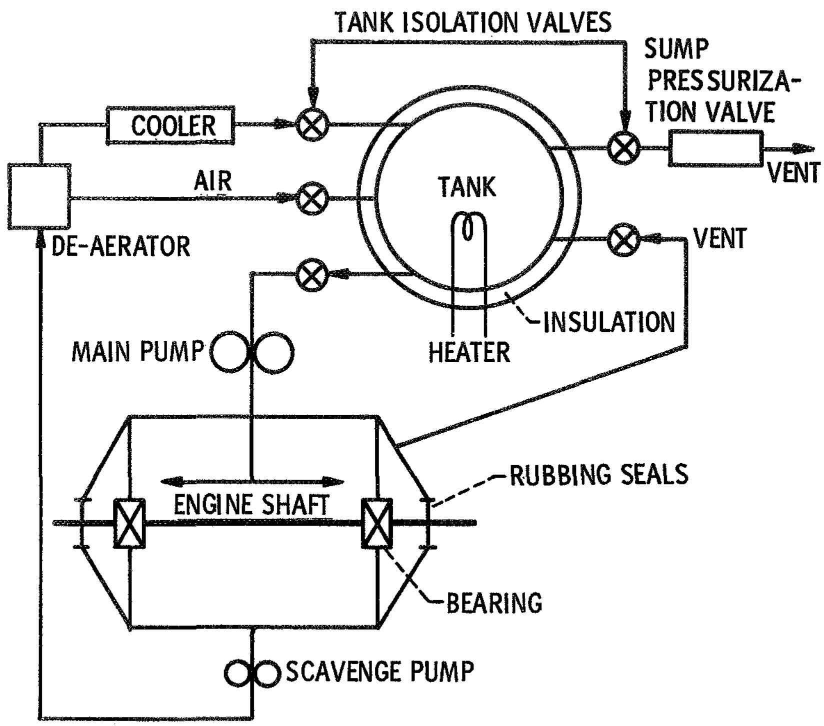


Figure 12. - Schematic of lubrication system (General Electric engine).

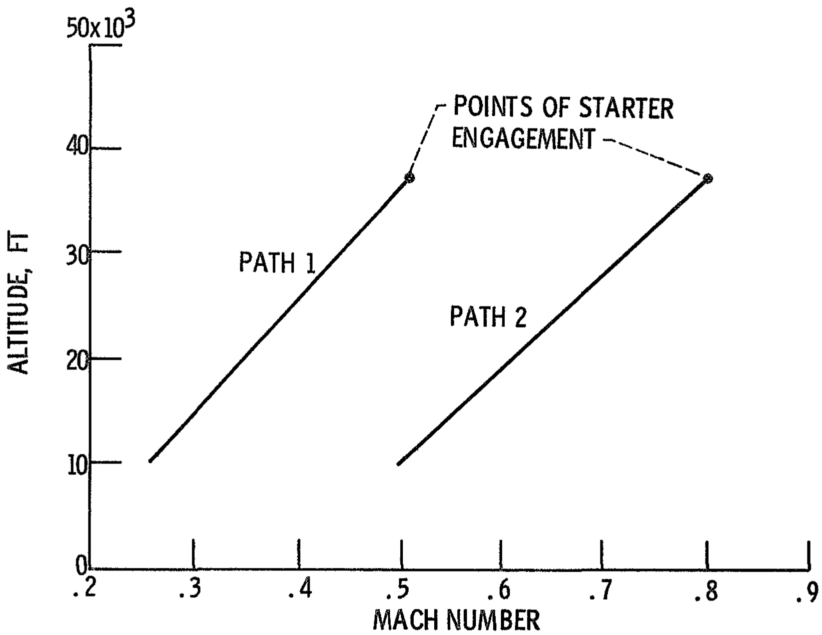


Figure 13. - Example reentry trajectories.

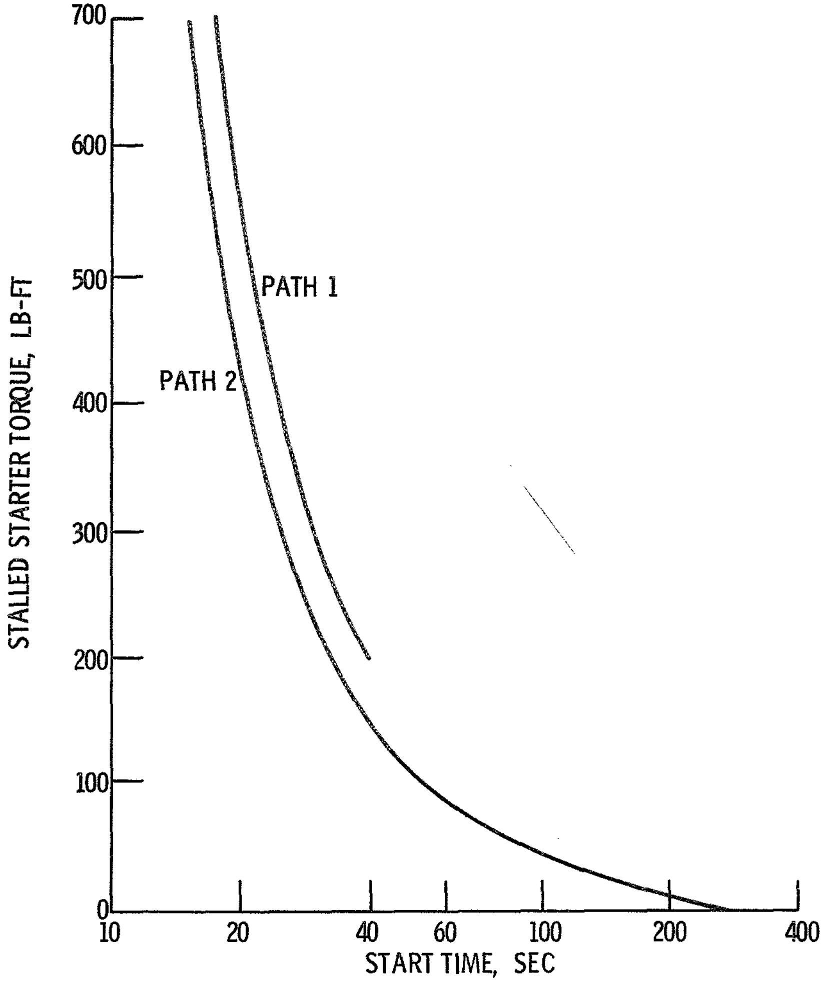


Figure 14. - Effect of start time on starter size (General Electric engine).

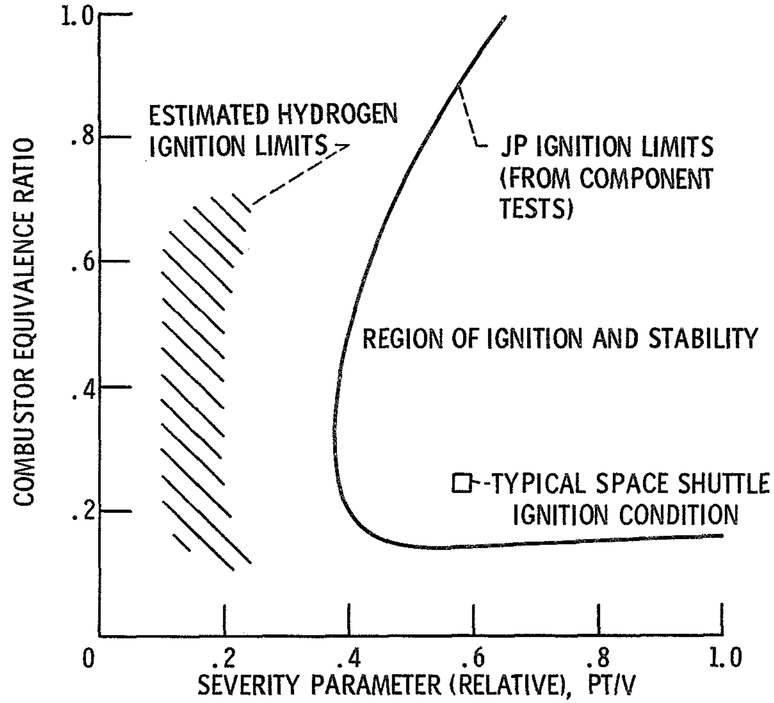


Figure 15. - Combustion stability limits (General Electric engine).